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Nuclear Materials & Propulsion Operation

INTRODUCTION TO NUCLEAR PROPULSION

Lecture 14 - REACTOR CONTROL APPLICABLE TO NUCLEAR SPACE CRAFT

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REACTOR CONTROL APPLICABLE TO NUCLEAR SPACE CRAFT

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INSTRUMENTATION AND CONTROL OF NUCLEAR ROCKETS FOR SPACE MISSIONS

Page

1. Basic Considerations which Determine Control System Requirements

Nuclear rocket propulsion has been considered for a number of space applications which can be conveniently classified in two groups.

Group I Unmanned Space Applications

(a) Upper stage vehicle such as the NERVA.
(b) Interceptor satellite for rendezvous inspection, recovery or destruction of a "target" satellite.
(c) Lunar ferry for soft landing of instrumentation and supplies on the moon.
(d) Venus and Mars satellite probes for investigating the atmosphere and surfaces of these planets.

Group II Manned Space Applications

(a) Manned reconnaissance vehicle for inspection, recovery, or destruction of satellites.
(b) Second stage Dynasoar type of orbital vehicle.
(c) Lunar Mission.
(d) Venus and Mars expeditions.

The above missions have varying functional objectives which establish the vehicle navigation and guidance requirements. Navigation and guidance systems in turn determine the thrust and attitude control system requirements and specifications.

Missions in Group I will likely represent the majority of space explorations in the next decade. No life support equipment is required and the navigation and guidance functions would be performed by automatic controls using information transmitted from earth tracking stations. They will be less expensive than manned vehicles and sufficient to accomplish most reconnaissance and scientific objectives. The unmanned vehicle must be completely automated with a minimum number of simple functional systems in order to do the job reliably and reduce the unloaded vehicle weight.

Manned missions will require manual emergency controls and a small display of important engine measurements. This additional instrumentation and control will allow the astronauts to monitor the rocket engine and attitude control system and provide a means of returning to earth if some of the automatic controls should fail.

To launch a satellite into a predetermined circular orbit requires very close control of thrust cutoff time and vehicle attitude. These requirements are equally important in rendezvous missions. Startup time must be relatively fast for upper stage nuclear vehicles such as proposed for NERVA. Figure 1.1 shows that startup times of 30 to 40 seconds can be achieved using a reactor period of about 1 second.

Rendezvous missions executed by a nuclear powered vehicle already placed in orbit have only slightly different startup requirements. The initial startup to a low power such as 10 kilowatt can be performed more slowly. At this low power level the reactor may be maintained in a critical state indefinitely if the power generated is radiated into space without exceeding component design temperatures. However, the startup time to go from a reactor power of 10 kw to about 1000 mw (5 decades) would have to be performed reasonably fast. This is true because the time of the vehicle velocity change is of some importance in performing rendezvous missions and because it is desirable to operate at conditions of maximum specific impulse to reduce propellent consumption.

To make a rendezvous, velocity increment, position, and firing time may be computed and transmitted from earth tracking stations. The guidance receives the decoded information from the telemetry unit and stores the information in command registers. Before the firing position is established the reactor startup is initiated. The reactor follows a programmed startup. The vehicle navigation system continuously computes the velocity which is compared to the value in the command register. Thrust may be terminated before the desired velocity increment is established to allow for aftercooling the reactor.

The first several aftercooling pulses may be used to provide additional thrust to increase the velocity increment. After the velocity increment is attained, the vehicle attitude control system could orient the rocket nozzle radially away from the earth. Additional aftercooling pulses would then have less effect on the vehicle trajectory. These aftercooling pulses may also be used for mid-course guidance if correction information is computed and transmitted from earth tracking stations.

2. A Summary of Some Propulsion Control System Requirements

Studies of propulsion requirements for a number of space missions were performed at North American Aviation and published in References 1, 2, and 3. Table 2.1 is a summary of some results from their studies.

Table 2.1 shows that the thrust to deliver a desired payload and to perform different missions varies widely. Propulsion velocity increments are especially critical if midcourse guidance maneuvers are not available. There is a considerable range in thrust to earth-weight ratios which will perform various orbital transfer and orbital correction maneuvers.

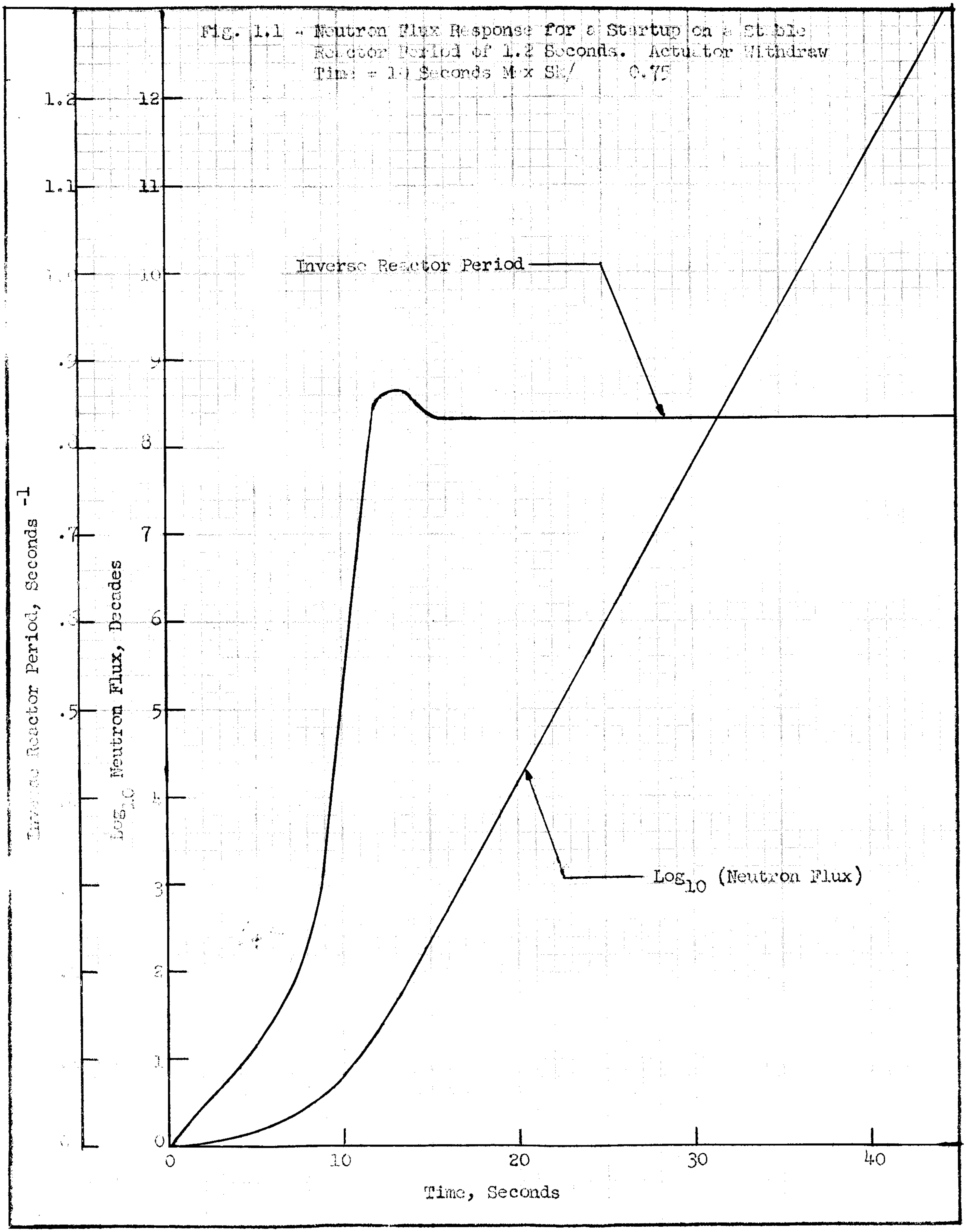


Fig. 1.1 - Neutron Flux Response for a Startup on a Stable Reactor Period of 1.2 Seconds. Actuator Withdraw Time = 10 Seconds Max Sk/ 0.75

Planetary soft landing (hovering maneuvers) require rather precise thrust control to maintain a constant velocity descent. However, nuclear propulsion may not be adopted for landing maneuvers but may be restricted to orbital transfer (and rendezvous) missions where the vehicle remains in orbit and the cargo, propellant, and crew are transported to and from the earth by chemical rockets. Radiation hazards that might occur during re-entry and landing are thereby avoided.

Velocity increment control rather than exact thrust control is important to establish a desired orbital rendezvous mission. The time integral or the thrust to mass ratio establishes the required velocity increment. The most important requirement in propulsion control is that of being able to measure velocity and terminate the thrust quickly and accurately. A good medium range terminal guidance system will increase the nominal velocity cutoff tolerances at the expense of greater required payload weight and a little more propellent consumption. This, however, may be the only practical method of rendezvous using nuclear rockets because of the aftercooling requirements.

Propulsion control system requirements for most nuclear rocket applications may be summarized in the following statements.

1. The nuclear powered rocket must be capable of start and restart in a reasonable period of time. Desirable startup time should range from 15 to 60 seconds to attain good velocity increment timing.

2. A selective programmer will be required to translate information from the navigation and guidance system to the thrust control system.

3. The programmer must have complete control of an automatic system for starting and shutdown the reactor and propellent feed system.

4. For manned spacecraft, an emergency control system which can override a part or all of the automatic system appears highly desirable. An astronaut can often make decisions based upon information not available to a computer. In addition he would then have provisions for making corrective action if an automatic control system fails.

5. Thrust control programming during startup and shutdown is not critical. Velocity increment is the desired end result and thus a predictable thrust cutoff time is of far more importance. The reactor shutdown should be performed rapidly from the low thrust level defined in item 10.

6. Time duration of applied thrust is of some importance so that only the first and most predictable aftercooling thrust pulses may be used to increase or decrease the desired velocity increment. Midcourse guidance may possibly make use of additional aftercooling pulses.

7. For performing rendezvous missions a terminal guidance system will be required to compensate for the inaccuracy of the navigator and for error in velocity cutoff timing. Midcourse guidance is highly desirable and may be necessary to perform long range rendezvous missions. Midcourse guidance requirements are determined by the effective range of the terminal guidance system.

8. After applying thrust with a nuclear rocket, it will become radioactively hot. The nuclear rocket is likely to have only a shadow shield so that it will be necessary to orient the vehicle properly during rendezvous if the target is not to be exposed to radiation. This may impose rather severe requirements on the attitude control system.

9. Good attitude control system response will be required if forward and retrothrust is achieved by use of a single rocket engine with only one nozzle. A separate retrothrust unit is highly desirable for performing rendezvous missions.

10. A two level thrust control system with a fixed transition time will satisfy most of the mission requirements. This type of program is also a desirable one for making a reactor startup and shutdown. Aftercooling requirements are reduced and thrust cutoff time to achieve a given velocity increment is less critical. A 6 to 1 step variation in thrust is suggested in the Rocketdyne Studies in order to perform all the desired maneuvers.

11. To prevent reactor temperature damage after rocket engine cutoff, some type of aftercooling system is required. There are two basic considerations involved; the aftercooling control should minimize propellant consumption and provide vernier control of velocity to establish the desired velocity increment. This may mean providing thrust spoilage and attitude control so that subsequent aftercooling pulses are applied radially with respect to the center of mass of the planet.

There are many other detail requirements which are related to the reliability of control systems and their auxiliary power units which are not considered here.

TABLE 2.1

Thrust and Velocity Increment Requirements
for Various Missions and Maneuvers

I. Earth Orbital Rendezvous

Considers only close earth rendezvous for assembly of long range vehicles.

Thrust	10,000 lb
Thrust/Weight Ratio	.05
Velocity Increment	~2800 ft/sec
Velocity Increment for 5° change in orbit plane	2200 ft/sec

Velocity increment requirements to rendezvous with target satellites as far out as a 24 hour orbit are considerably greater depending upon the parking orbit altitude as shown in Figure 2.1, 2.2 and 2.3.

II. Lunar Landing and Return Mission

Two stage LO_2/LH_2 rockets

Thrust	100,000 to 200,000 lb	First Stage
Thrust/Earth Weight	0.35	
Thrust	77,000 lb	Second Stage
Thrust/Earth Weight	0.68	

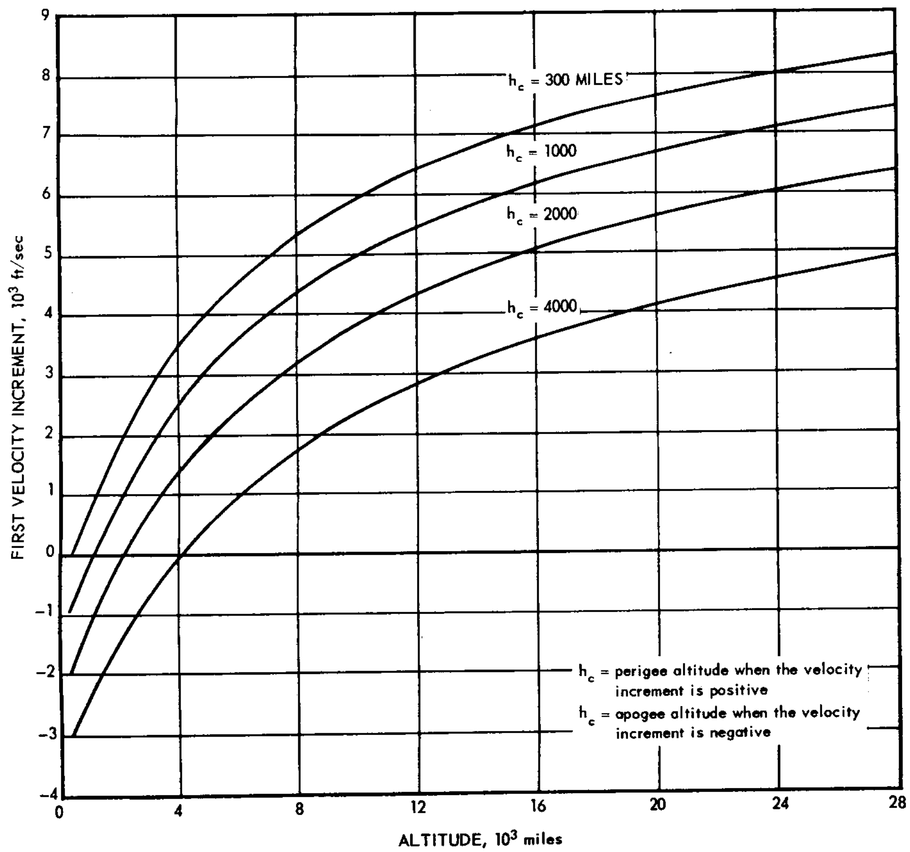


Fig. 2.1 – Velocity increment to be added to a circular, orbit with altitude, h_c, to create an elliptical orbit whose perigee or apogee altitude is given on the abscissa

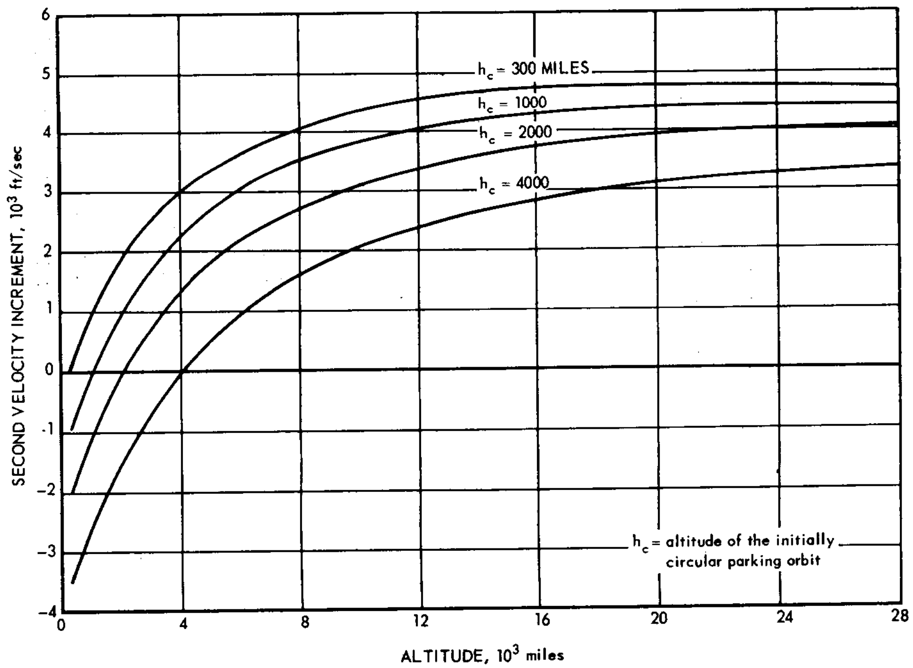


Fig. 2.2—Second velocity increment added to the elliptic orbit at the altitude given on the abscissa to create a circular orbit at that altitude

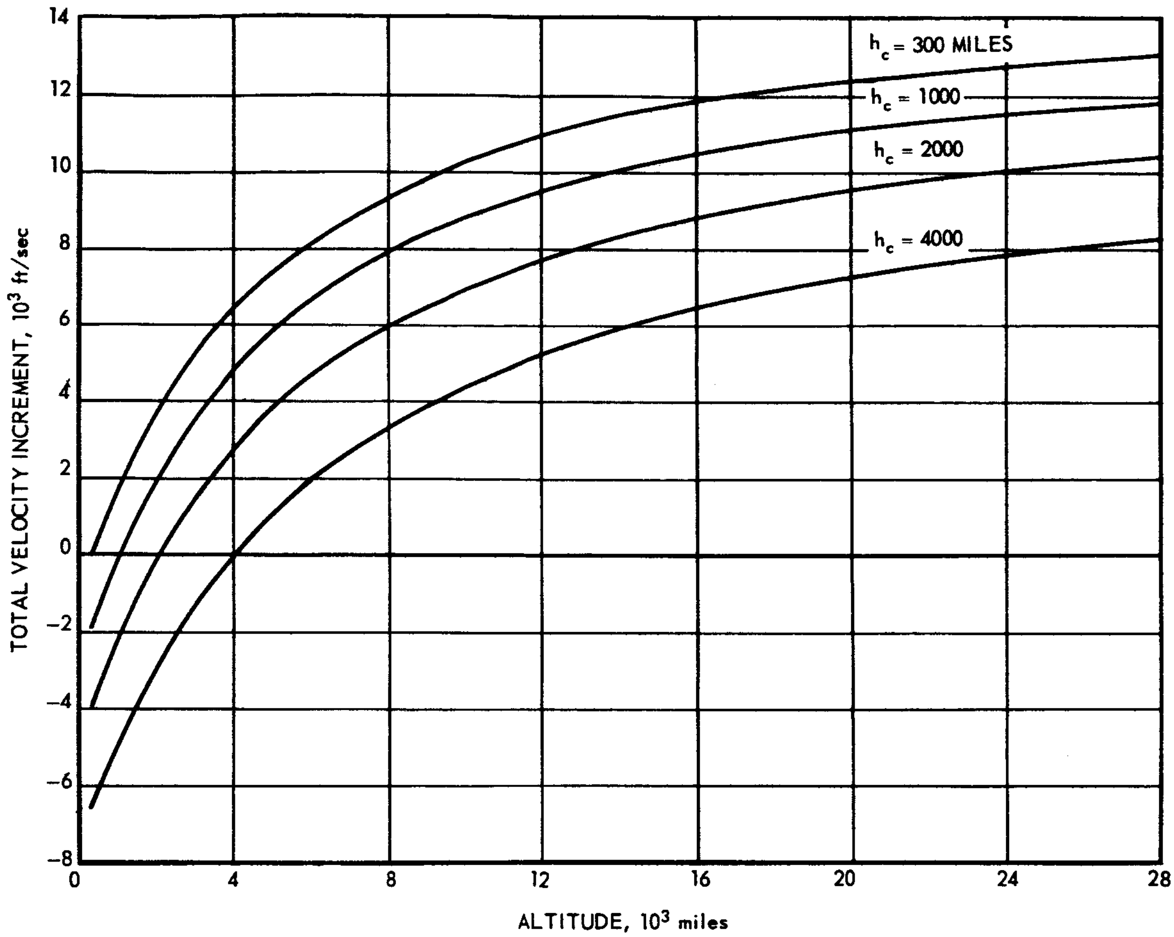


Fig. 2.3 – Total velocity increment required to convert a circular orbit of altitude, h_c, to a circular orbit whose altitude is given on the abscissa

<u>For Direct Lunar Landing</u>

Thrust	200,000 to 300,000 lb	First Stage
Thrust/Earth Weight	0.70	
Thrust	40,000 to 80,000 lb	Second Stage
Thrust/Earth Weight	1.5	

III. Earth to Mars Transfer with 300 n Mile Orbit Around Mars

Space Vehicle Weight	350,000 lb in orbit
Transfer Time	200 days
First Stage Engine	Thrust = 150,000 lb thrust
	Thrust/Weight = 0.5
Second Stage	Thrust = 30,000 lb

If transfer time were reduced one half, thrust requirements would increase greatly. Energy level of the transfer varies inversely with trip time.

IV. Planetary Transfer Maneuvers (Venus and Mars)

Velocity Increment	10,000 to 20,000 ft/sec
Thrust/Weight	0.3 to 0.8

V. Lunar Transfer Maneuvers

Velocity Increment	10,000 to 11,000 ft/sec
Thrust/Weight	0.1 to 0.8

VI. Lunar Orbit Establishment and Departure

Velocity Increment	≈ 3240 ft/sec
Thrust/Weight	0.1 to 0.5

Based on these preliminary studies, thrust/earth weight ratios for leaving or establishing an orbit about the earth, moon, or planets can be arbitrarily selected within the limits given below:

Earth	0.3 to 1.5
Moon	.06 to 0.5
Venus	0.2 to 1.2
Mars	0.1 to 1.0

Within these limits propulsion maneuver velocity increments do not change greatly.

For the hovering phase in the landing mission the thrust to earth weight ratio is critical and the values required at the end of the propulsion landing phase are given below:

Earth	1.0
Moon	0.17
Venus	0.87
Mars	0.39

3. Propulsion Control System Operations

Thrust control systems may be defined to include all sequence and control equipment necessary to start and preheat the reactor, raise reactor power, and meter propellent flow so that precise control of vehicle velocity increment is possible. This includes also the control subsystem for engine shutdown and aftercooling of the reactor. For convenience the following operations are classified with respect to the sequence performed.

Reactor Startup - This operation makes the reactor critical and raises the reactor power to a safe temperature level so that the power generated is consumed by radiation into space and by thermoelectric or thermionic power units which may be installed. This phase of operation then establishes the reactor core temperature at a level which is not detrimental to any part of the engine. Time required to perform this operation - 30 seconds to 5 minutes, depending on the application. The hold time at this level may vary from minutes to days.

Engine Startup - This part of the operation raises reactor temperature and introduces propellent flow at a rate which provides high specific impulse and complies with reactor design limitations. When the engine power range thrust system has complete control, this phase of the operation terminates. Time required - 20 or 30 seconds to start turbopumps and raise reactor power by the required 4 or 5 decades.

Engine Thrust Control - This part of the operation includes all the time in which the power range thrust control system is in complete command. Selection and timing of the thrust program is controlled by the guidance system based upon vehicle velocity and position information. Time required - 1 to 20 minutes, depending upon the application.

Engine Shutdown and Aftercooling - When thrust cutoff time has been determined with due allowance for thrust that will be generated from aftercooling, the reactor is either shut down or reduced to negligible power levels. Thrust is gradually reduced before cutoff for reasons given previously. Afterheat power may then be removed periodically by pulse cooling the reactor. Pulse duration and repetition rate may be controlled from temperature measurements or by sequence timing based upon the time integral of reactor power.

4. Control System Measurements

The main function of the engine control system is to obtain a high average specific impulse consistent with reactor design limitations, and to modulate and terminate thrust so that the correct velocity is attained at the right time to perform a desired maneuver. Rocket engine performance is directly related to the total temperature and pressure of the hot gas at the nozzle inlet. For a fully expanded nozzle it is well known that the specific impulse is directly proportional to the $\sqrt{T/\bar{m}}$ where T = total temperature of the reactor discharge gases and $\bar{m}$ is the equivalent molecular weight of these gases. For nuclear rockets, hydrogen propellent is used so that $\bar{m}$ = 2 if the gas is not dissociated to an appreciable extent. This compares with 8 to 12 for a chemical LOX - Hydrogen rocket burning with a rich hydrogen mixture. Reactor materials have a limited design temperature which for solid core reactors produces a lower discharge gas temperature than is possible from chemical rockets. Nevertheless a gas discharge temperature of 4000 to 4500^{o}R can be achieved from heat transfer nuclear rockets.

Reactor power and propellant flow rate determine reactor discharge gas temperature and pressure which then determine the rocket engine performance, assuming we have a fixed geometry nozzle and propellent inlet temperature. Basically we then have five measurements that may be used to control the rocket engine in all phases of its operation. These five include, reactor wall temperature, reactor discharge gas temperature, reactor power, reactor discharge pressure, and propellent flow rate. These measurements are not easily accomplished and the accuracy of any feed back control system is directly dependent upon its measuring sensors. Even though we have an "optimum" automatic control system, the accuracy of the system is no better than the sensors.

Another aspect of automatic control is concerned with other parameters which are used for control even though they may not be measured directly. We change reactor power by temporarily increasing or decreasing the reactivity or excess multiplication factor. Turbopump speed can be used for control system stabilization and as an indirect measure of propellent flow if the pump characteristics are known and do not change with operating time. We then have six or seven variables which we may consider for automatic control systems excluding the accelerometer measurements. A summary of the measurements that may be used in the guidance and engine control system is given below.

Engine Control Measurements

1. Q = Reactor Power, Megawatts
2. δk = Reactivity
3. $\dot{W}_p$ = Propellent Flow, lb/sec
4. T_c = Reactor Discharge Temperature, ^{o}F
5. $\bar{T}_f$ = Fuel Element Surface Temperature, ^{o}F
6. N_t = Turbospeed, RPM
7. P_c = Reactor Discharge Pressure

Guidance System Measurements

1. Linear Acceleration, ft/sec^2
2. Linear Velocity, ft/sec
3. Linear Position, ft
4. Angular Acceleration, rad/sec^2
5. Angular Velocity, rad/sec
6. Angular Position, radians

We now consider some of the problems associated with measuring the engine control variables.

4.1 Reactor Power, Megawatts

Neutron flux measurements have conventionally been used as an indication of reactor power. Fission chambers are used for low flux measurements while the ion chambers are used for high power measurements. Ion chambers have a rapid response time with a time constant of at least 10 milliseconds due primarily to capacitance of the ion chamber, its cables, and input circuitry. An ion chamber responds to all mechanisms producing ionization. Most of the signal is derived from the $_{5}B^{10}+_{0}N^{1}$ reaction. However the location of the chamber with respect to the reactor determines the collector signal current. The chamber should be so located that its signal is proportional to reactor power and not dependent upon the position of the drums or control rods, the propellent flow, or temperature of the reactor. Figure 4.1 shows a typical arrangement for a small nuclear rocket. Geometrically the ion chambers would have to be located in the front shadow shield to avoid interaction from the above effects. Even then there will be some variation between ion chamber signal and reactor power but this can be reduced to a small percentage error. The ion chamber creates an undesirable void in the shield. Fast spectrum reactors require a moderator surrounding the ion chamber to increase its sensitivity and reduce the void volume.

A gamma compensated ion chamber may be used with logarithm instrumentation to extend its range over 6 decades. Below this level, the reactor may yet be critical so that some type of sensor is required to measure extremely low neutron levels. Fission or pulse type chambers can be used but the circuitry must collect random pulses of low frequency, hence the response time is longer than for an ion chamber. For fast spectrum reactors this low range instrumentation may not be required once a reactivity calibration has been established. (Reactivity in the low power range does not change much from fission product buildup.)

Both fission chambers and ion chambers have been designed to operate up to $1000^{o}F$, but the electronic instrumentation for processing these signals are presently limited to a temperature of less than $600^{o}F$. Solid state sensors and circuits have been developed which are small and require less electrical power but they operate reliably only at lower temperatures. These components would have to be installed in a controlled temperature environment.

Flux measurements are most useful in controlling a reactor startup but the instrumentation and power supplies represent a weight penalty and help lower the reliability. For rocket applications these startup units should be reduced in number and used for controlling relay or switching operations. Ion chamber current can directly control a small bistable flip flop circuit without additional amplification.

4.2 Reactivity, δk

At any given time reactor control rods or drums can be calibrated in terms of reactivity with accurate ground based nuclear instrumentation. This reactivity calibration will not change greatly with operating time if a fast spectrum reactor is used. Reactivity calibration may then be used to make subsequent reactor startups without low level nuclear instrumentation and has the potential of controlling temperature before the engine startup is initiated. If the reactor calibration is performed in simulated space chambers the designated control elements could be calibrated in terms of temperature assuming the reactor is designed with a negative coefficient of reactivity.

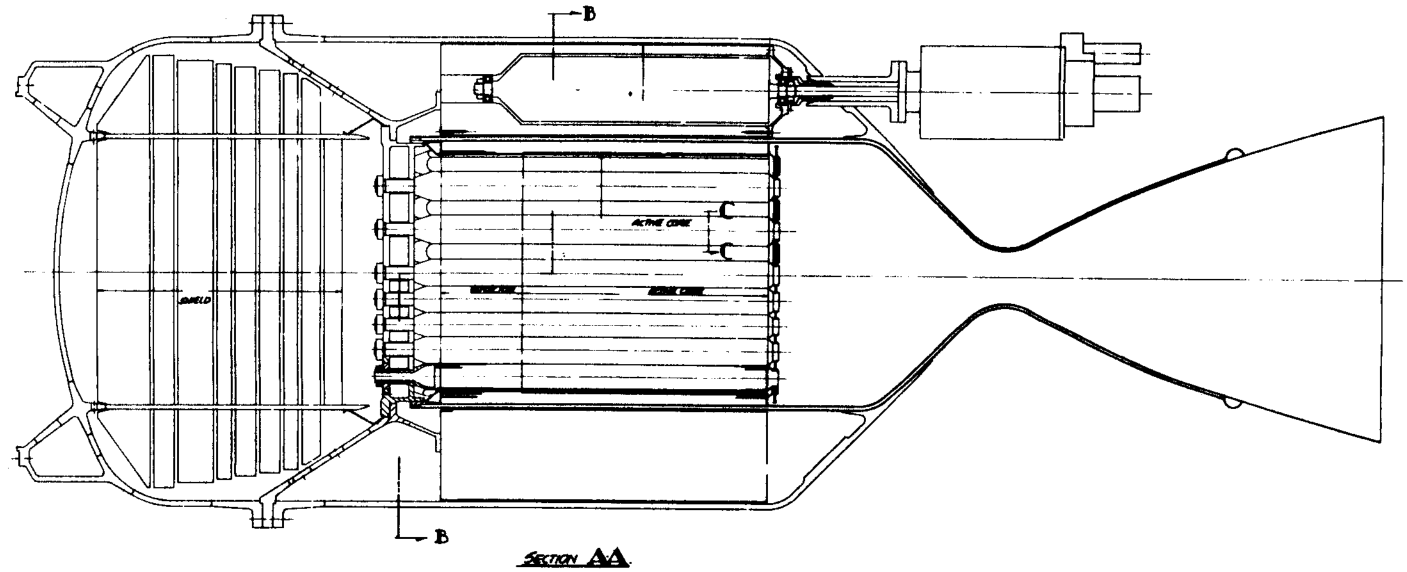


Fig. 4.1 – A typical rocket engine configuration

For cold startup applications it is desirable to have a given set of drum positions correspond to a given stable reactor period within $\pm$ 50%. In addition the startup reactivity should be limited to $\delta k/\beta < 0.9$. As shown in figure 4.2 this will provide a sufficiently rapid startup time and yet provide safe operation using physically realizable actuators.

4.3 Propellent Flow

Although accurate flow measuring transducers have been developed for metering conventional turbojet fuels there is much more work needed to meter cryogenic fuels accurately. Mass flow measuring instruments for cryogenic fuels must operate at extremely low temperatures and yet when they are not in use they will be exposed to normal ambient conditions. Mass flow measuring instruments will not likely exceed an accuracy of 1% especially when operating under conditions of vibration and thermal shock that is associated with the propellent feed system of a rocket engine. If reactor power and propellent flow could be measured accurately there is a strong incentive to use these measurements in a thrust control system. By scheduling reactor power and propellent flow the reactor discharge temperature and pressure are controlled indirectly without the use of high temperature sensors.

If the turbopump characteristics do not change with time, then it would theoretically be possible to measure the pressure head and speed of the pump and determine propellent flow. However the entire flow of the pump may not be passing through the reactor at all times. This is especially true if a surge by-pass valve is required for operating in the low flow region or a part of the propellent is used for other purposes.

4.4 Reactor Discharge Gas Temperature

For a highly expanded nozzle the reactor discharge temperature determines the specific impulse obtained from the hydrogen propellent. Gas temperatures and external surface temperatures may be measured directly with Tungsten - Tungsten Rhenium thermocouples. Thermocouple leads would have to penetrate the pressure wall and be large enough to withstand the abuse of mechanical vibration and hot gas erosion. Large junctions add thermal inertia which increases response time and may introduce inaccuracy due to thermal conduction.

To reduce the response time the thermocouple may be installed in the throat of the nozzle or a small stream may be bled from the reactor discharge and expanded to ambient in a miniature nozzle composed of thermocouple materials. The throat of the nozzle may be constructed of two materials such as tungsten - tungsten rhenium. Heat transfer at a nozzle throat is high which greatly improves the thermocouple response time. Resistance elements may be used instead of thermocouples. A self balancing bridge potentiometer would then measure the temperature.

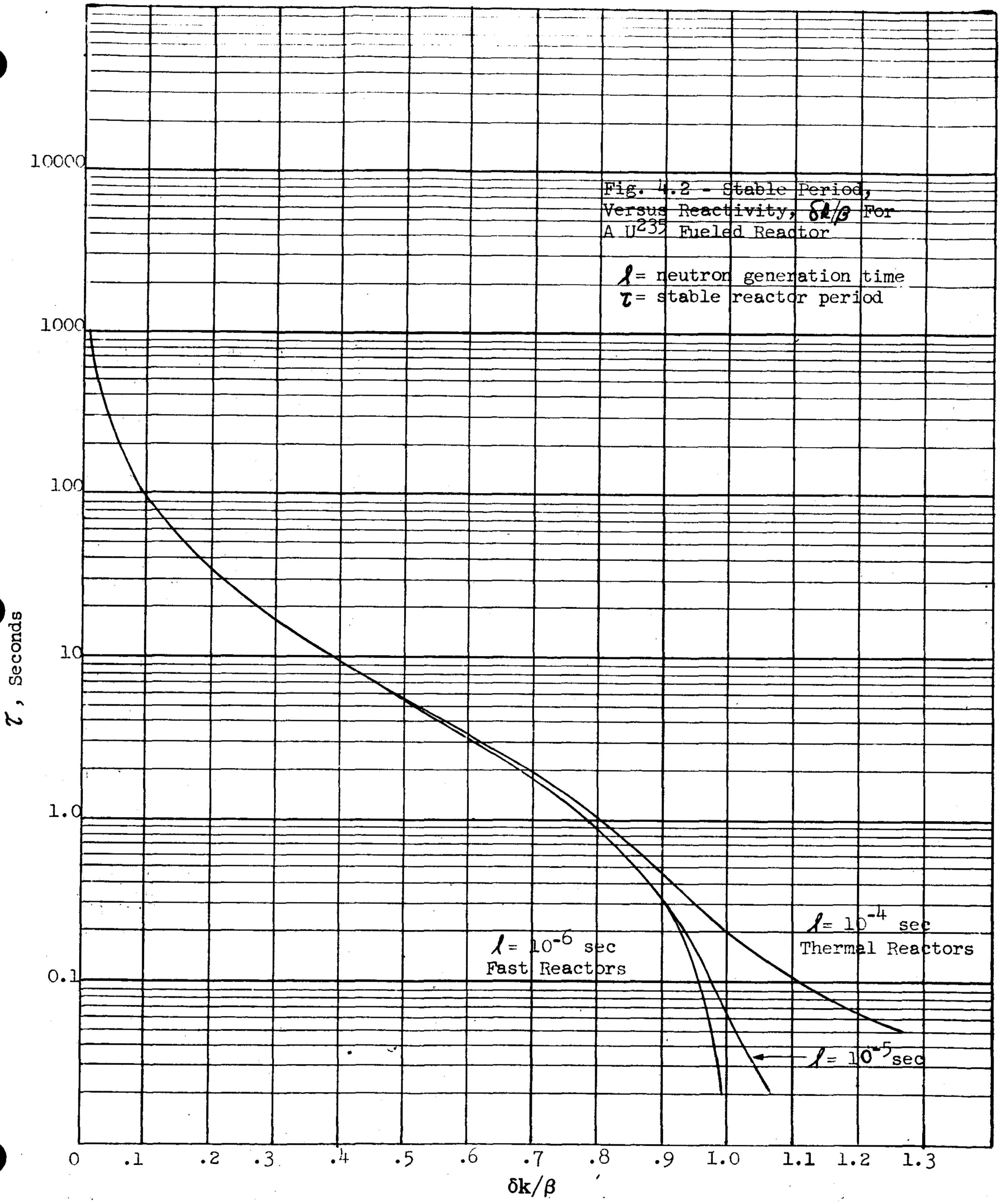


Fig. 4.2 - Stable Period, Versus Reactivity, δk/β For A U235 Fueled Reactor
l = neutron generation time
τ = stable reactor period
l = 10-6 sec
Fast Reactors
l = 10-4 sec
Thermal Reactors
l = 10-5 sec
10000
1000
100
10
1.0
0.1
τ, Seconds
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
δk/β

Hot gas temperature is really but an indirect measure of the limiting reactor fuel temperature. Furthermore gas discharge temperature is not very effective for aftercool control of the reactor. The most desirable measurement is the fuel temperature of the reactor itself.

4.5 Reactor Surface Temperature

Any reactor core is temperature limited so that in principle it would be desirable to measure and control on the hottest core temperature. Usually the hottest part of a reactor can only be estimated from calculations because they are inaccessible to experimental measurements.

There are several possible methods of determining fuel temperature. Some of these are as follows:

(1) Measure the thermal expansion of the core.
(2) Measure the energy radiated from a hot surface.
(3) Measure the voltage from a thermoelectric junction attached to the fuel material.
(4) Measure the change in resistance of a fuel element.

Position displacement measurements of the core require high temperature transducers or some form of optical viewer. Position transducers have been designed for operation in ambient temperatures up to 1200°F which means that transducers would have to be located near the inlet to the reactor or be cooled by the liquid propellent. A number of electrical leads would have to penetrate the pressure shell and be adequately shielded for protection against the environment. If an optical viewer were used, one may as well use an optical pyrometer which would probably be required for calibration of the position transducer in the first place.

An optical pyrometer can be used for accurate temperature measurements of an accessible surface. An oblique viewer may possibly be mounted on the converging part of the nozzle so that a measure of the rear hot surface of the core is obtained. More than one instrument may be used to increase the reliability without much weight penalty. The infrared lens system would have to be cooled and there is a mechanical problem of penetrating a hot and cold zone through the nozzle wall. The assembly must be able to withstand full nozzle inlet pressure.

The millivolt signal from thermocouples require considerable amplification to be effective in an automatic control system. However there is much to be gained by making temperature measurements since this is the critical parameter in aftercooling as well as during engine startup and full power operation. Laboratory thermocouple and optical pyrometer measurements can be made with an error of $\pm 1\%$ but in rocket applications this accuracy would be difficult to achieve.

4.6 Turbopump Speed

Speed measurements can be made very accurately and the resulting measurement provides an excellent rate signal for stabilization purposes. Propellent flow control can be achieved by use of a throttling valve and by turbine speed control. Since the throttling valve introduces a wasted pressure head it is desirable to use this valve only as a vernier or not at all. The turbine speed loop then acts as the main propellent control. A surge control by-pass valve may be necessary to prevent pump operation in the surge region. Pump speed and pressure head is used to control the by-pass valve.

The most desirable propellent flow control is to schedule turbopump speed using the speed error signal to actuate the turbine power control valve. Pressure or propellent flow may then be measured and used to trim the speed schedule if more accurate thrust control is necessary.

Speed may be measured by use of many different types of tachometers. One convenient method is to rotate a gear tooth wheel and use a magnetic pickup to provide a frequency proportional speed. The frequency of the voltage from the magnetic pickup can then be digitized easily if necessary.

4.7 Reactor Discharge Pressure

Reactor discharge pressure is a good measure of engine thrust. If propellent flow can be accurately measured and reactor temperature cannot, then the discharge pressure may be used to trim a scheduled reactor flux during the power range operation.

High pressure measurements of a hot gas are difficult to achieve and the usual approach is to cool the gas which directly contacts the transducer. The entire transducer may be cooled by the liquid hydrogen flowing in the regeneratively cooled nozzle. Pressure may also be measured at the reactor inlet or at some intermediate lower temperature point if the pressure drop across the reactor is known and does not change with time.

There are many types of pressure sensors designed for operation at normal temperatures. Strain gage transducers are used frequently. Piezoelectric crystals and solid state detectors provide a voltage signal when a force of pressure is exerted upon preferred faces of the crystal but are subject to radiation damage. Some pressure sensors use the displacement of a diaphragm or spring loaded piston. Differential transformers and variable reluctance transducers then supply an electrical signal. Better accuracy is attained if force feedback returns the diaphragm or piston to a neutral position. The feedback force is then a measure of the pressure.

5. Reactor Startup Characteristics

For rocket applications the reactor must be capable of making a fairly rapid startup. The reactor time behavior is determined by the delayed neutron precursors. These delayed neutron emitters govern the exponential rise in neutron flux for a given positive value of reactivity, δk. The exponential process is characterized by the growth rate, $1/\tau$, where τ is the stable reactor period or time constant. The stable reactor period is related to reactivity by equation (5.1) (Reference 4).

$$\delta k = \frac{\ell}{\ell + \tau} + \frac{\tau}{\ell + \tau} \sum_{i=1} \frac{\beta i}{1 + \lambda_i \tau}, \tag{5.1}$$

where β_i = delayed neutron fraction of the i th group,
λ_i = decay constant of the i th group of delayed neutron emitters,
and ℓ = the neutron generation time.

Figure 4.2 shows the relation between τ and δk for several different generation times. Note that for a fast spectrum reactor the period, τ , becomes very short as $\delta k \to \beta$. However, if $\delta k \leq 0.8\beta$ there is little difference between fast spectrum and thermal energy reactors. The inverse reactor period is also related to the reactor flux as given by equation (5.2).

$$\frac{1}{\tau} = \frac{1}{\phi}\frac{d\phi}{dt} = \frac{d}{dt}(\ln\ \phi) = 2.30\ \frac{d}{dt}\log_{10}\phi \tag{5.2}$$

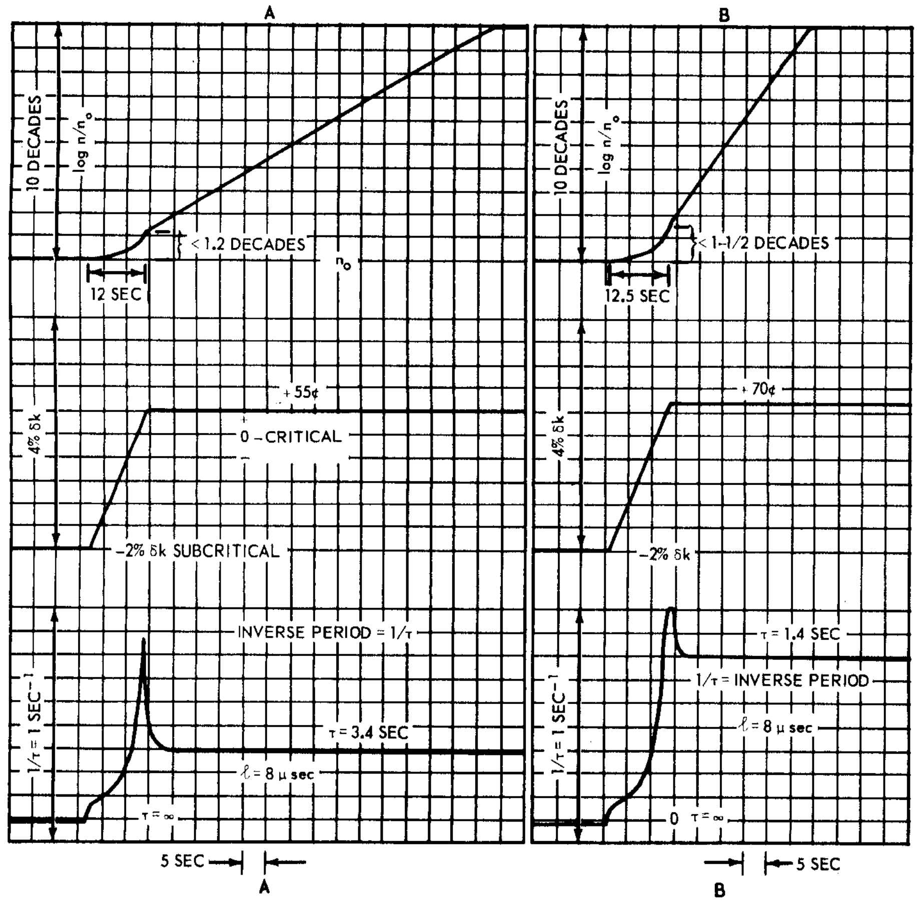
The inverse period is then proportional to the slope of the log flux trace. Figure 5.1 shows a time recording of the log ϕ, δk, and $1/\tau$.

After the initial transient the stable reactor period, τ , determines the time, t, required to increase the neutron flux from some level, ϕ_o, to some higher level, ϕ, in accordance to equation (5.3).

$$t = 2.30\ \ \tau \log_{10}\ \phi/\phi_o \tag{5.3}$$

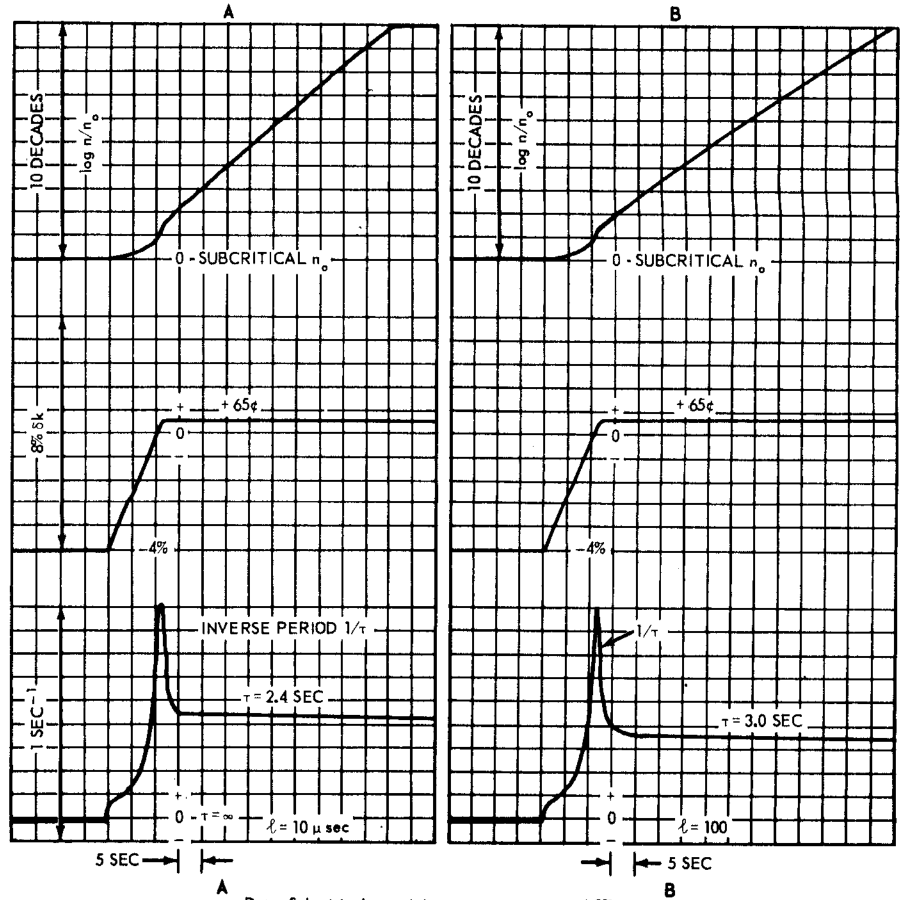
Although the period is relatively independent of the neutron generation time when $\delta k < 0.8\beta$ it becomes highly dependent on this parameter as $\delta k \to \beta$.

Figure 5.2 shows that for a ramp withdraw of reactivity there is an initial flux rise of a little over one decade while the reactivity is inserted. There is a transient overshoot in the inverse period which exceeds the stable inverse period by a considerable amount. The overshoot can be greatly diminished by reducing the reactivity rate after $\delta k > 0.3\beta$ as shown in figure 5.3. The rise in neutron flux



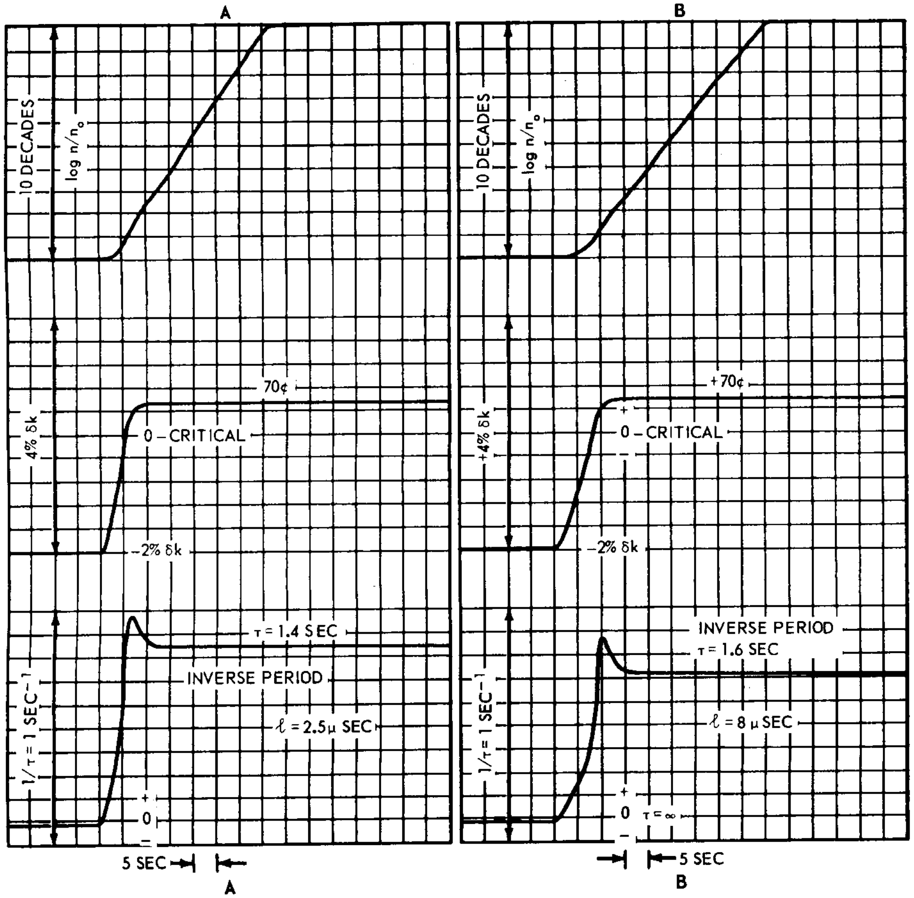
Data:		
Subcritical reactivity		–2.0%
Positive reactivity clamp	A = 55¢	
	B = 70¢	
Ramp reactivity rate		0.2%/sec
Neutron generation time		8.0 μ sec
Stable reactor period	A = 3.4 sec	
	B = 1.4 sec	

Fig. 5.1 – Effect of maximum positive reactivity clamp on stable reactor period



Data:		
Subcritical reactivity		–4.0%
Positive reactivity clamp		65.0¢
Ramp reactivity rate		0.4%/sec
Buffer time constant		0.1 sec
Neutron generation time	A = 10 μ sec	
	B = 100 μ sec	
Produces stable reactor period	A = 2.4 sec	
	B = 3.0 sec	

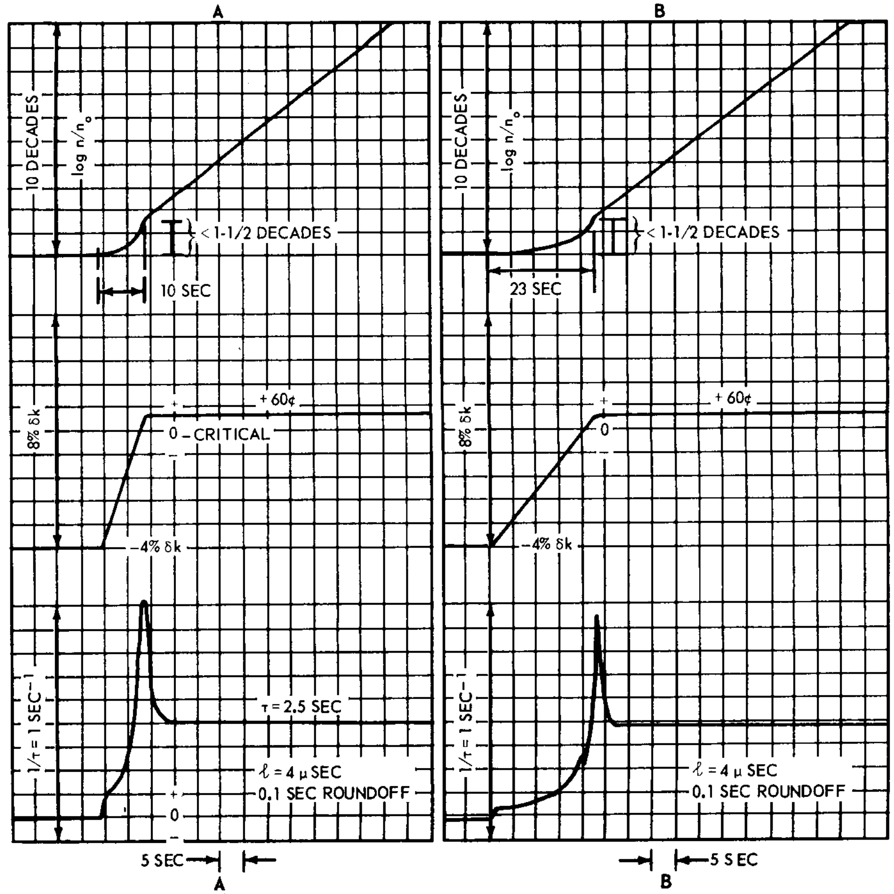
Fig. 5.2 – Effect of a ramp change in reactivity on the transient inverse period, 1/τ



Data: Subcritical	–2.0%
Positive reactivity clamp	70.0¢
Reactivity rate	A = 0.40%/sec
	B = 0.27%/sec
Buffer time constant	1.0 sec
Neutron generation time	A = 2.5 μ sec
	B = 8.0 μ sec
Produces stable reactor period	A = 1.4 sec
	B = 1.6 sec

*The log simulator defined in Appendix A cannot be used to investigate conditions when $\ell \leq 1\ \mu$ sec. For fast reactors $\ell \leq 1\ \mu$ sec the stable periods of interest are dependent only upon $\delta k/\beta$ (see Figure 12).

Fig. 5.3 – Effect of neutron generation time on stable reactor period



Data: Subcritical reactivity	–4.0%
Positive reactivity clamp	60¢
Reactivity rate	A = 0.50%/sec
	B = 0.19%/sec
Buffer time constant	0.1 sec
Neutron generation time	4.0 μ sec
log n/n_o during reactivity insertion	A ~ 1.4 decades
	B ~ 1.4 decades
Stable reactor period	2.5 sec

Fig. 5.4 – Effect of reactivity rate produces negligible change in n/n_o during reactivity insertion time

during the withdraw time is fairly independent of the rate of inserting reactivity and the initial subcritical reactivity as shown in figures 5.4 and 5.5. As a consequence a relatively simple means of computing the time necessary to start the reactor for short withdraw times can be determined by equation (5.4).

$$T_s = T_w + 2.30\,\tau\left[(\log_{10}\phi/\phi_o) - 1.1\right] \tag{5.4}$$

where T_s = reactor startup time, seconds

T_w = actuator withdraw time, seconds, $T_w < 30$ sec.

ϕ = desired level of the neutron flux

ϕ_o = source level of the neutron flux

$\tau(\delta k/\beta, \ell)$ is given by figure 4.2.

From figures 4.2 and 5.1 through 5.5 we draw the following conclusions:

1. For both fast spectrum and thermal energy reactors a rapid but safe startup can be achieved if the maximum positive reactivity limit, $\delta k \leq 0.8\,\beta$ where β = total delayed neutron fraction.

2. Within the limitations of item 1, the reactor flux can be increased 10 decades in 30 to 40 seconds.

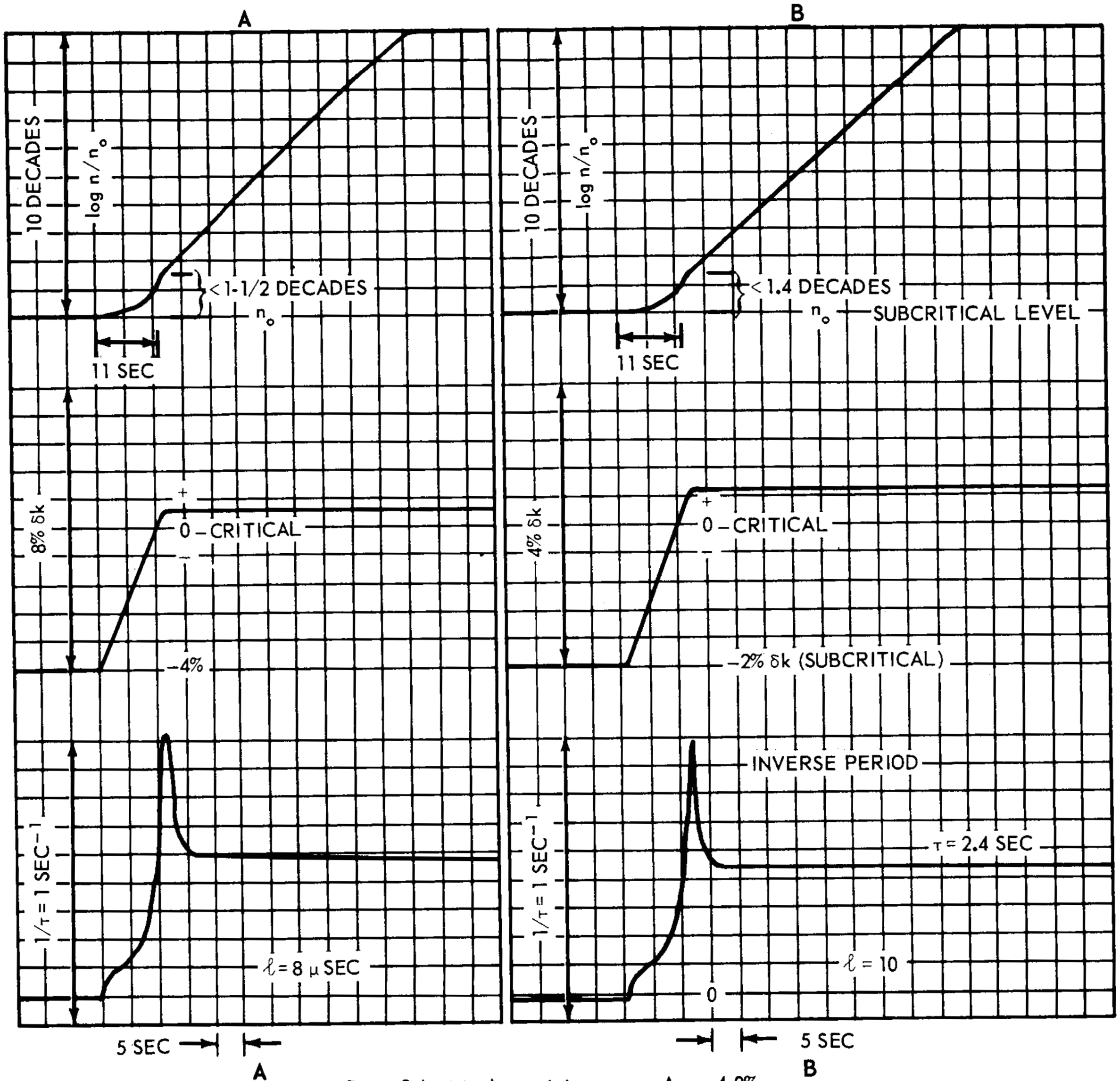
3. The first 1.4 decades of flux rise occurs during the withdraw time of the actuators independent of the degree of subcriticality and the withdraw rates of interest for rocket applications.

4. A transient inverse period exists during the actuator withdraw time which may be 2 or 3 times the stable inverse period. The magnitude of the transient depends on the rate of change in reactivity after the reactor reaches criticality and on the maximum value of reactivity.

5. The transient overshoot can be greatly reduced by decreasing the reactivity rate when $\delta k > 0.3\beta$.

6. The reactor startup time does not depend upon the values of $\beta = \sum \beta_i$ if reactivity is expressed in terms of $\delta k/\beta$.

7. The stable reactor period determines how fast the neutron flux reaches the power range after the actuators cease to withdraw. It is a function of $\delta k/\beta$ and ℓ, the neutron generation time. The stable period is relatively independent of the neutron generation time if $\delta k/\beta$ 0.8 but becomes progressively more



Data:	Subcritical reactivity	A = – 4.0%
		B = – 2.0%
	Positive reactivity clamp	A = 65¢
		B = 62¢
	Ramp reactivity rate	A ~ 0.4%/sec
		B ~ 0.2%/sec
	Buffer time constant	0.1 sec
	Neutron generation time	A = 8 μ sec
		B = 10 μ sec
	Stable reactor period	2.4 sec

Fig. 5.5 – Effect of subcriticality on n/n_0 rise during reactivity insertion time (a very small effect)

dependent as $\delta k/\beta \rightarrow 1.0$ corresponding to prompt criticality.

There is a great danger that a reactor runaway will occur if $\delta k \rightarrow \beta$ even for thermal reactors, i.e., a reliable set of actuators are not usually fast enough to prevent damage without the aid of a strong negative temperature coefficient of reactivity. We may state that a reactor startup control is nothing more than a system for introducing the correct amount of δk and making sure that the reactor does not become prompt critical.

Reactivity cannot be measured directly but can be determined by measuring the inverse period or rate of change in log flux. Usually period instrumentation is used in a manual or automatic control system for starting the reactor. However, it is conceivable that this instrumentation could be used once to calibrate a program of drum positions versus reactivity or inverse period. If this set of relations did not shift greatly between reactor operations, subsequent cold reactor restarts could be made by merely withdrawing control drums to specified positions. After the neutron flux has advanced several decades, one set of compensated ion chambers could then be used for monitoring and controlling the reactor during the engine startup. This corresponds to a "blind startup" until the neutron flux has risen to an intermediate range where the ion chambers can provide a useful signal. This approach eliminates some fairly complex low level neutron instrumentation which would otherwise have to be carried aboard the space craft.

6. Turbopump Performance Characteristics

Before considering reactor and engine startup control systems let us examine the turbopump which is the heart of the propellant feed system. Turbopumps may be axial flow or centrifugal flow or combinations of the two. They all have some characteristics in common such as a surge region and a desirable operating region separated by a surge line.

Figure 6.1 shows a pump characteristic map where the pump pressure rise is plotted against propellant mass flow for various pump speeds as a parameter. A parabolic surge line separates the permissible operating region from the undesirable surge region. This surge line is somewhat a function of ambient temperature of the pump. If the pump and its inlet plumbing has been precooled, then only liquid hydrogen with no entrained vapor enters the pump. If prechilling by use of hydrogen bleed is required before starting the pump, a few additional control elements are required and the startup sequence must include the additional steps.

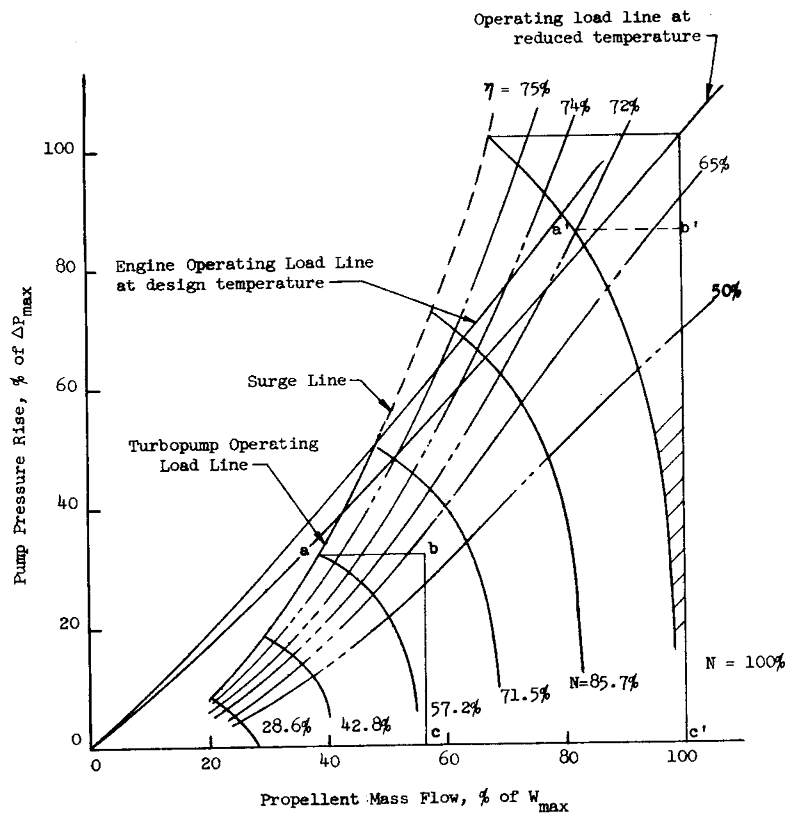


Fig. 6.1 - Non Dimensional Pump Characteristic Map

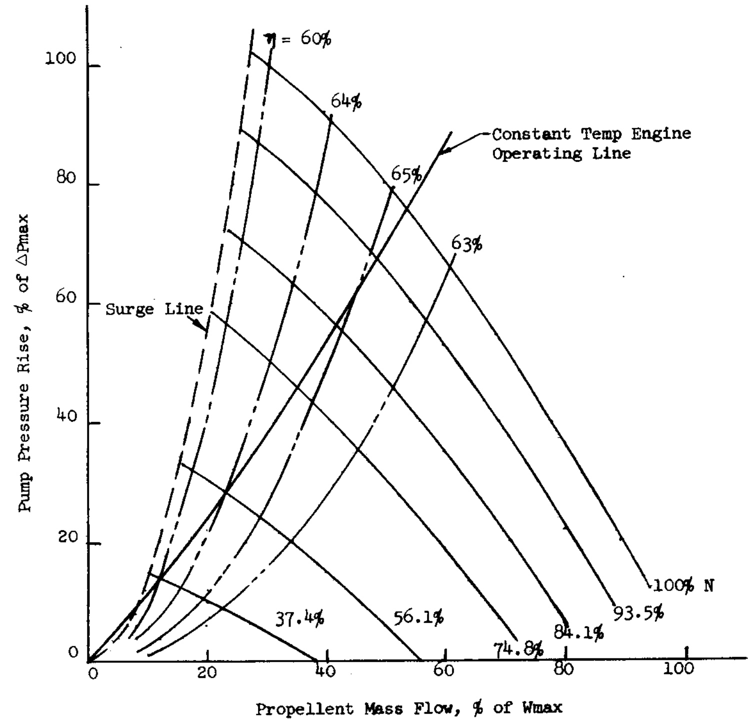


Fig. 6.2 - Non Dimensional Liquid Hydrogen Turbopump Characteristic Map

A turbopump adds energy to the propellant in terms of pressure rise and flow to overcome the pressure drop of the propellant feed lines, the reactor, and the exhaust nozzle. In normal operation the reactor discharge gas temperature is maintained nearly constant and the flow through the rocket nozzle is nearly proportional to the reactor discharge pressure. As a result of the choked nozzle flow, the reactor pressure drop is also approximately proportional to the propellant flow. Pressure drop in the feed lines, in the nozzle cooling jacket and the reflector varies more nearly as the square of the propellant flow.

If the feed system operating load line is drawn on the pump map as shown in figure 6.1 the line is more linear than parabolic as it would be if the pressure drop varied as the square of the propellant flow. As a result the load line intersects the surge line in the low flow region and it is not possible to operate in the most efficient pump region at all times. A surge by-pass valve may be used so that when the load line nears the surge line it automatically by-passes propellant around the pump. The pump operating line then follows just to the right of the surge line even though the engine load line lies in the surge region. By-passing propellant flow may produce vaporization of the propellant resulting in pump cavitation or vapor lock. Therefore, only a small part of the propellant may be by-passed for a limited time.

To reduce the by-pass propellant at low flow, turbopumps may be designed with a larger operating region and a smaller surge region at the expense of slightly lower pump efficiency. Figure 6.2 shows the pump characteristics when this approach is used. The engine load line now intersects the surge line in a lower flow region and requires less by-pass flow to operate in this region.

The slope of the engine operating line increases with temperature. During a startup or shutdown it is possible to operate at lower temperatures in the low flow region and pass rather quickly through this region. A throttling range of 5 or 6 to one appears quite feasible but if the range is increased to 10:1 the design problem becomes more difficult for both the reactor and the propellant feed system. (A stable flow pattern must be maintained through the reactor over a greater flow range which may involve a transition from turbulent to laminar flow.)

In the bleed type of turbine or "bootstrap" system, the energy delivered to the turbine depends upon the reactor discharge pressure. The reactor discharge pressure in turn depends upon the speed and hence the energy delivered to the turbine. As a result the turbine torque is limited and the turbine startup time requires 5 or 10 seconds. Figure 6.3 shows a typical engine acceleration transient using a temperature regulated reactor. Reactor temperature dips considerably for this large transient step in speed demand. It may be noted that during a rapid turbopump

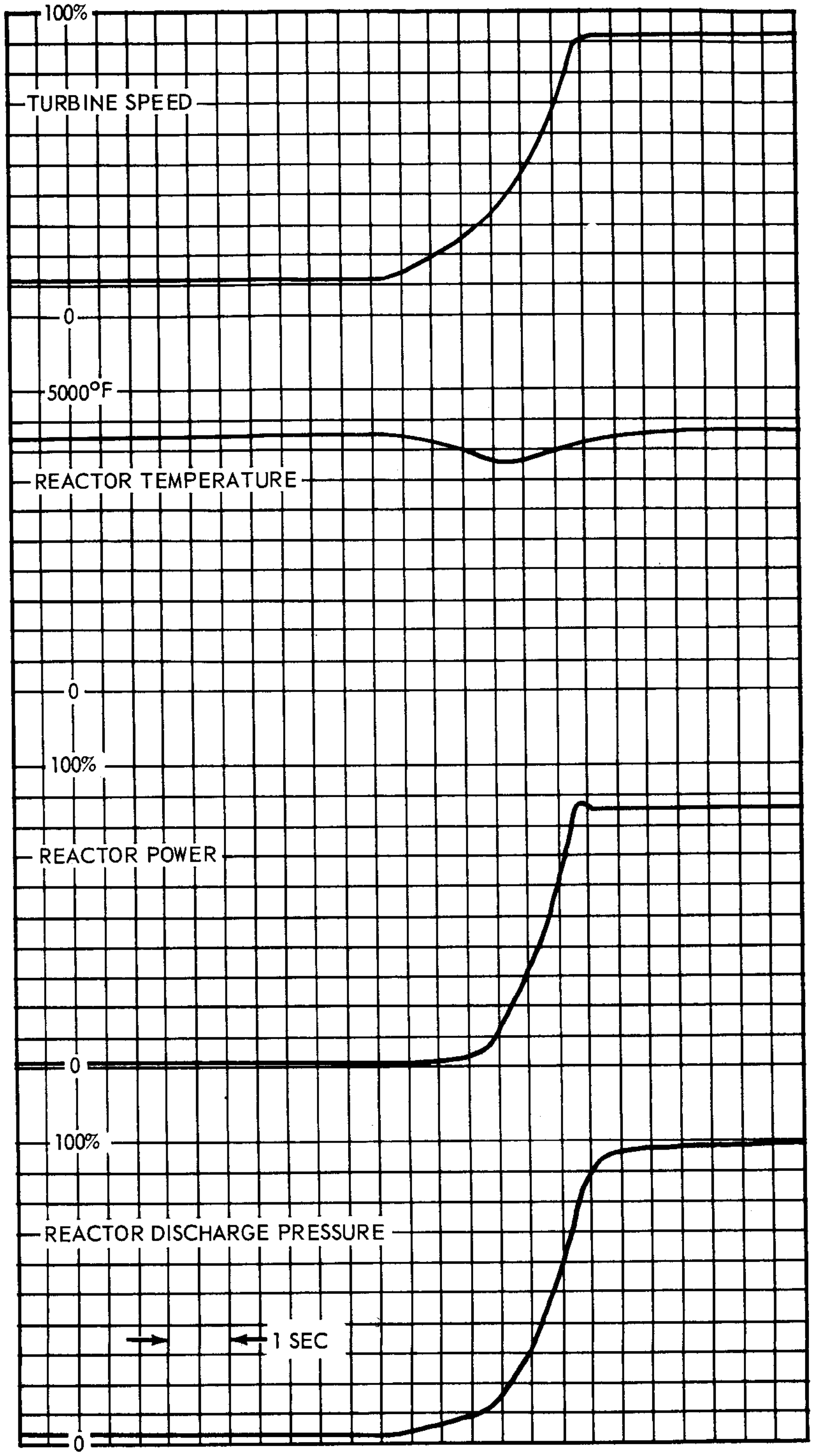


Fig. 6.3 – Typical turbine and reactor response traces to a large step change in demand

acceleration reactor power, turbine speed, and discharge pressure vary nearly exponentially with time. Possible acceleration limits may have to be imposed which would change the time behavior shown in this figure.

7. Reactor Drum Position Control

Certain subsystems are common to nearly all reactor startup and thrust control systems. Neutron flux or reactor power is controlled by positioning a number of drums. To maintain a fairly symmetrical power pattern the drums or control rods should be at the same position during steady state operation. This requirement can be achieved by either of the two following methods.

7.1 Incremental Stepping Motors

Open loop incremental stepping motors may be used and operated sequentially. The sign of the temperature or power error signal determines the direction of the stepping increment. No actuator is stepped twice in the same direction without the remaining actuators having been sequentially stepped once. Position loops are not required and the duty cycle of each actuator is greatly reduced. Analog computer studies of these systems show that good stability and performance is attained when they are properly designed.

7.2 Continuous Torque Motors with Position Feedback

An alternate method, which is widely used today, consists of using continuous rotary actuators driven by electrical, hydraulic or pneumatic torque motors. Each actuator contains a position sensor connected to form a position feedback loop. These position loops may be considered to be subsystems of a more complete control system. The temperature or flux error signal supplies the demand level to all position loops as shown in figure 7.1. Every actuator then follows the demand signal so that corresponding positions are attained during steady state operation. This method has been developed extensively using proven components and is the most likely approach to be adapted for use in nuclear propulsion.

7.3 Drum Position Loop Dynamics

For rocket applications the drum position loops should be fairly responsive. Analog computer studies show that drum position loops with the following characteristics are satisfactory for most rocket applications.

Natural frequency, Wn	25 to 30 radians/sec.
Damping ratio, δ	0.4 to 0.6
Reactivity rate limits	10 to 20% δk/min.
Proportional δk position limit	$\pm$ 0.35% δk max.

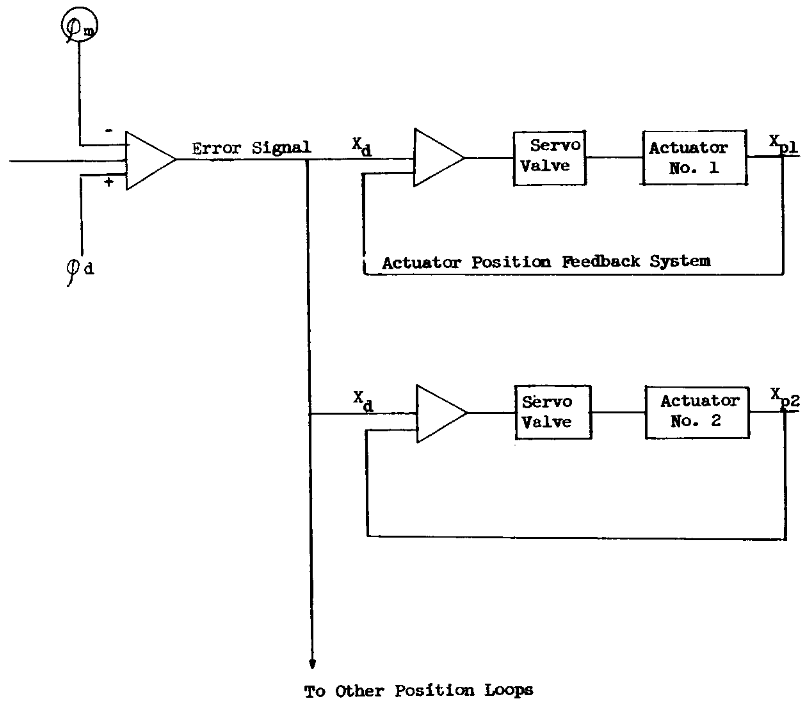


Fig. 7.1 - Position Loop Method of Forcing Independent Actuators to be in the Same Relative Position During Steady State Operation

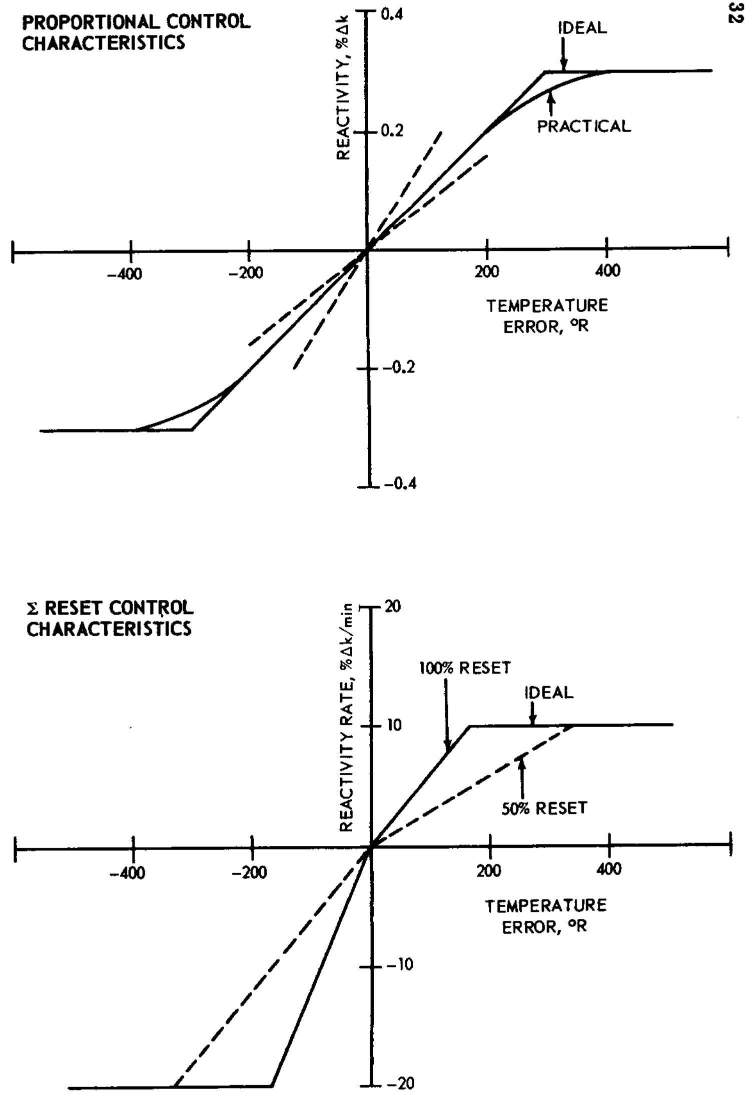


Fig. 7.2—Reactor temperature controller characteristics

These characteristics are expressed in terms of an equivalent second order system, the position loops are actually designed with components which yield higher order systems. These position loop requirements would not be difficult to attain if the environment could be reasonably controlled. Actuators for use in spacecraft will be subject to a cryogenic environment during operating time but may have to "soak" at some fairly high temperatures during the after cool period. They must be capable of making a number of restarts so that a large number of maneuvers are possible.

From the above requirements it may be noted that $\pm$ 0.35% δk max. is fairly low, but in some systems the corresponding actuators are capable of rapid motion. There is not much to be gained by making this larger when the reset drums have rate limits of 10%/minute or more, and there is an advantage in limiting the value from a safety point of view. Better response can be achieved if the demand signal to drum position loops are biased in gain and rate limited to favor a power reduction such as shown in figure 7.2. A gain variation of 2:1 helps reduce the temperature error considerably during a rapid reduction in power. The nonlinear gain can be readily achieved in the electrical part of the control system.

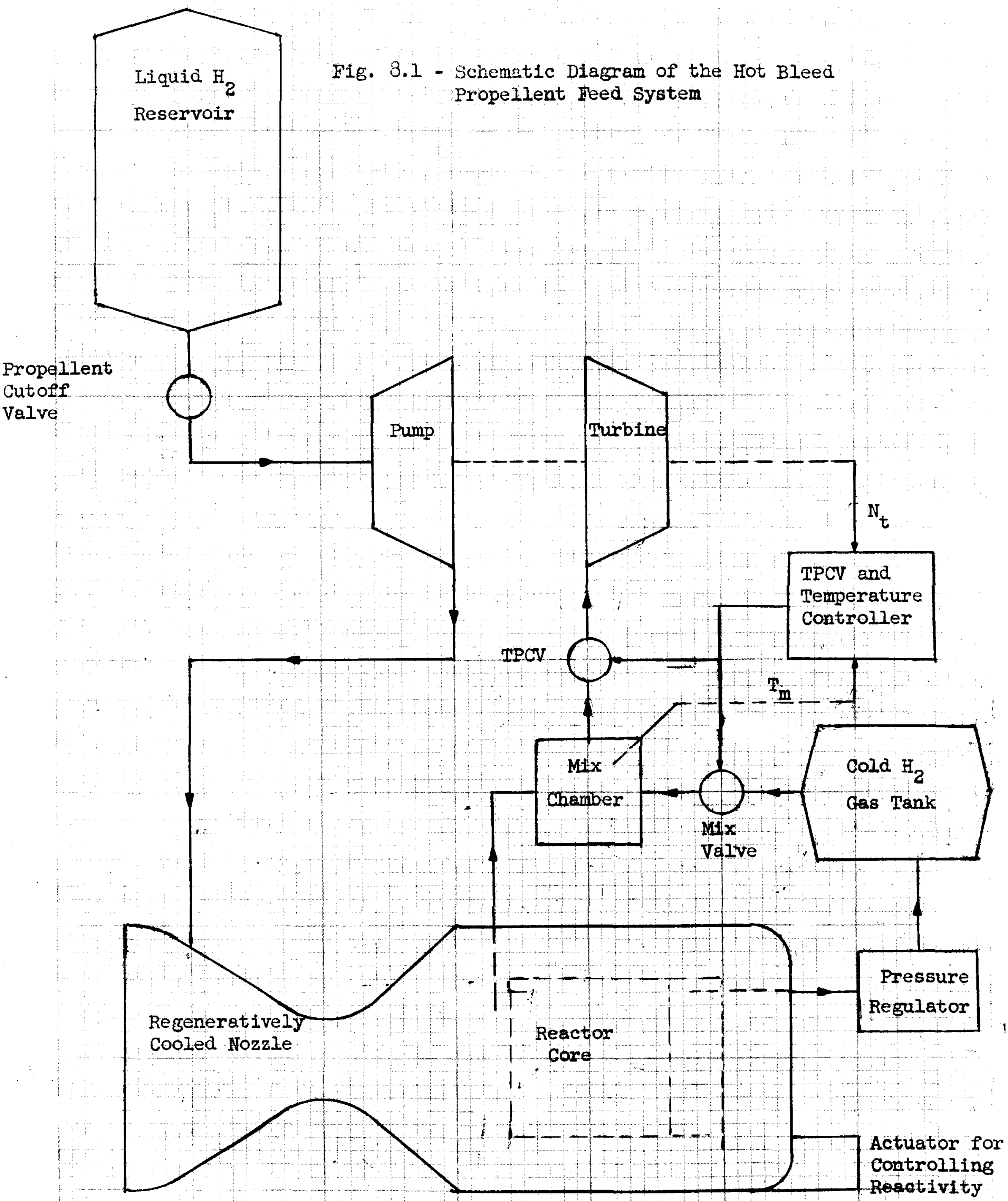
8.0 Typical Control Systems

We now consider two control systems which exemplify some of the points discussed previously. These two control systems have identical propellant feed systems shown in the simplified diagram of figure 8.1. Initially the turbine is started from cold gas and after the engine startup begins the hot gas is extracted from the reactor and mixed with cold gas. The turbine power control valve (TPCV) transfers the gas flow from the cold gas reservoir to hot stream delivered from the reactor after the engine startup begins. In addition the TPCV is used to modulate the hot gas flow to the turbine.

Temperature of the gas is regulated by a mix control valve shown in figure 8.2. In addition a surge valve controller is shown in this figure. The surge line can be expressed in terms of turbine speed or mass flow. For example $\Delta P_S = KW_p^2$ or $\Delta P_S = f(Nt)$ may be used to determine the surge pressure. This is then compared to the actual pressure rise plus a small bias safety margin. If the actual pressure rise plus the safety margin exceeds ΔP_S then the surge by-pass valve is opened proportionally.

Figures 8.3 and 8.4 show the main features of the control systems to be considered in this section. The first system uses a logarithmic flux loop and the second one a quasi logarithmic potentiometer to achieve gain compensation. A mechanically operated neutron attenuator may be inserted between the neutron sensor

Fig. 3.1 - Schematic Diagram of the Hot Bleed Propellent Feed System



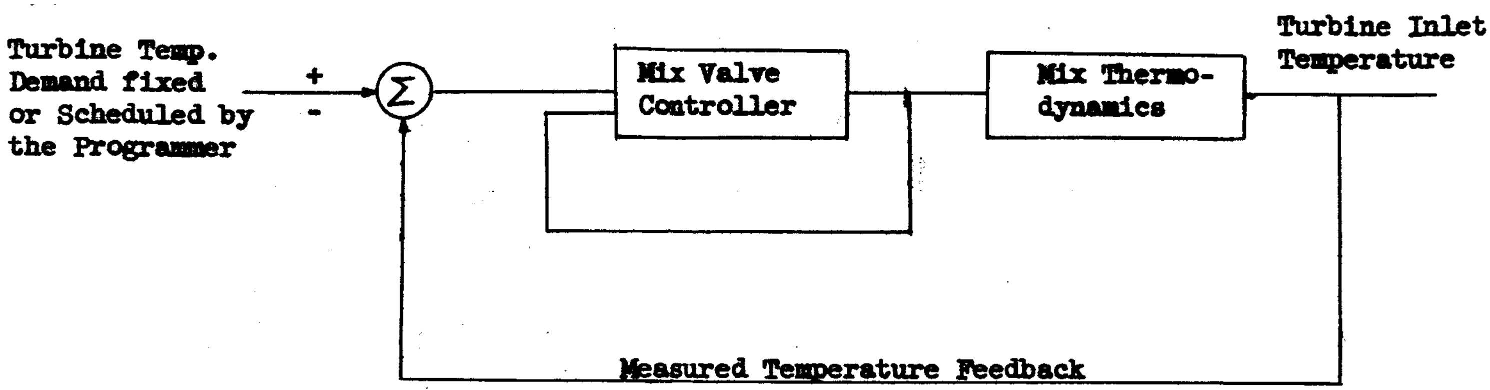


Fig. 8.2A - Block Diagram of Turbine Temperature Control

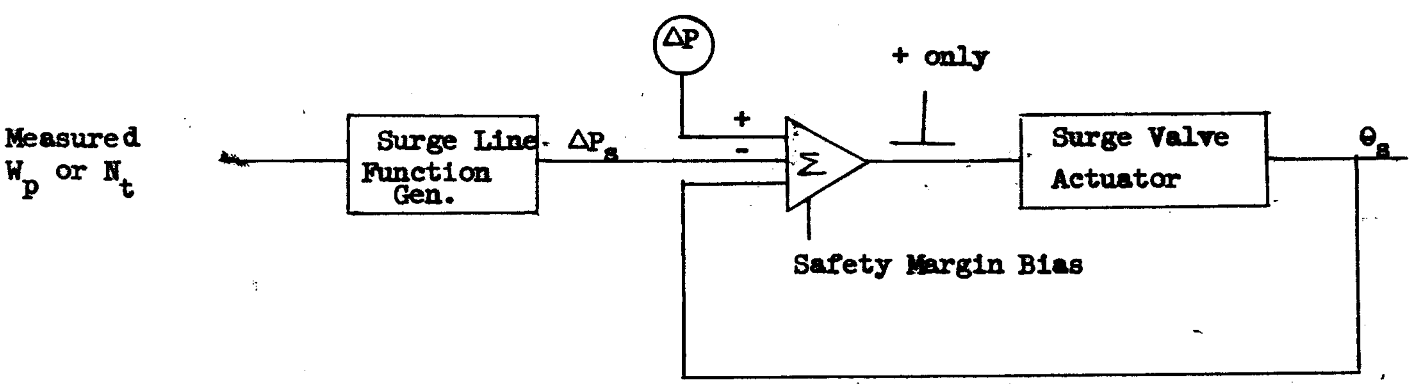


Fig. 8.2B - Block Diagram of Surge Valve Control

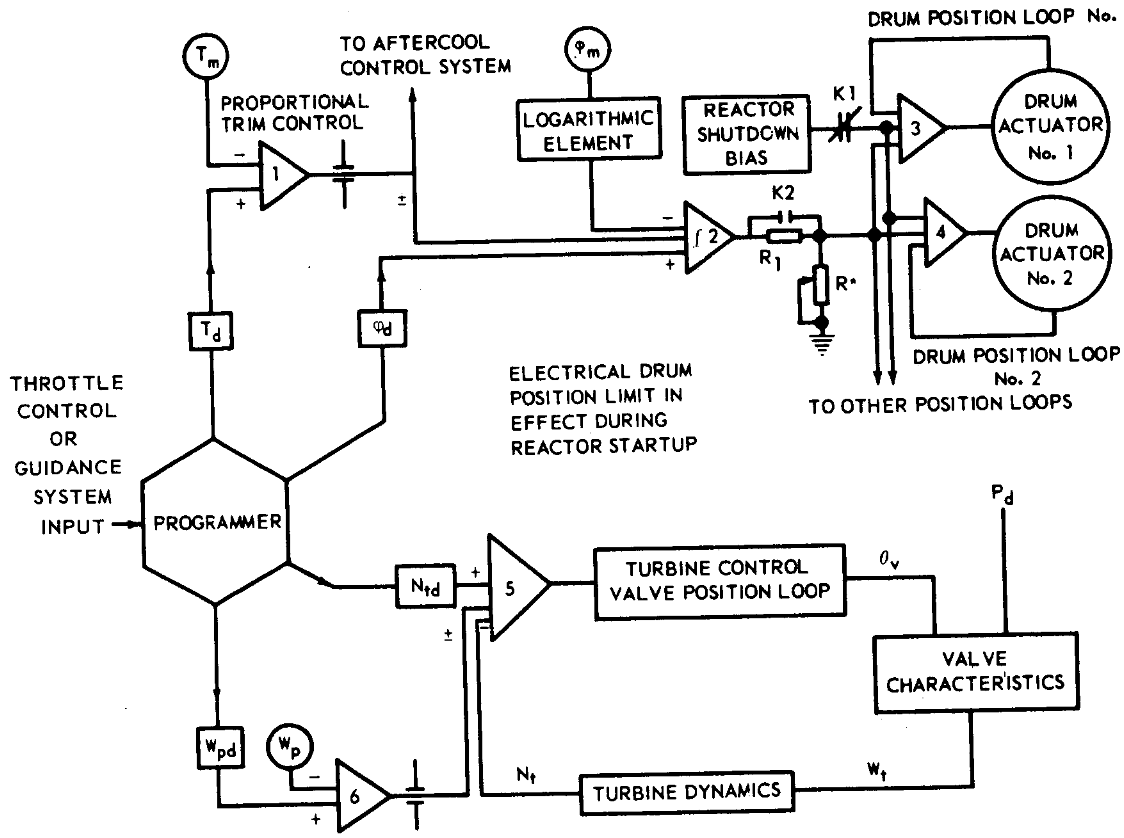


Fig. 8.3 – Schematic diagram showing basic elements of system No. 1

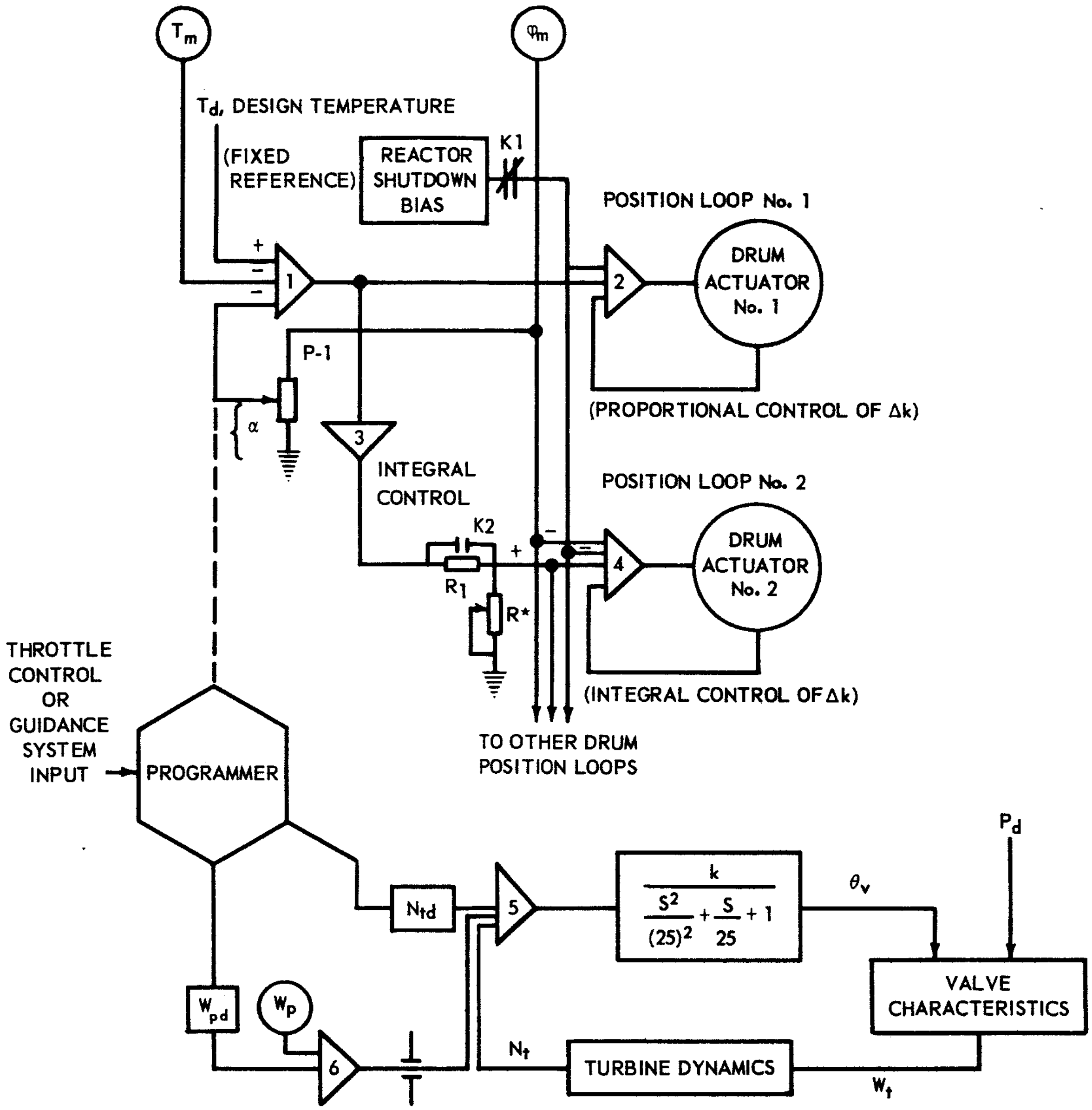


Fig. 8.4 – Schematic diagram showing basic elements of system No. 2

and the reactor core. The potentiometer then becomes a position actuator but the principle is still the same. In the latter system the flux measurement is faded out, while the thermodynamic measurement gradually takes control. In the first arrangement the flux measurement remains in the system at all times. Operation of these systems is now described in more detail with the use of relay contacts to show logic functions. Solid state switching may be used in practice to perform the logic operations

System No. 1 of figure 8.3 is representative of a class of systems which schedule reactor power and turbine speed. The turbine is mechanically coupled to a pump which provides propellant flow. Thermodynamic parameters are used for trim control of reactor power and turbine speed. Propellant flow is shown as the speed trim control and temperature measurements as the reactor power trim control. Other thermodynamic parameters may also be used for control purposes. The choice of thermodynamic parameters will depend upon which measurements can be performed continuously, accurately and reliably. Both arrangements provide good stability if the control system loops have the correct gain settings.

Startup is based upon having previous reactor experience. Low level startup instrumentation is used to calibrate the reactivity elements so that position of the actuators and reactivity relationships have been established. The lower level instrumentation is then no longer required unless reactivity versus drum position shifts considerably between operations. This shift in reactivity should be small for fast reactors so that for these reactors a part of the startup instrumentation may be eliminated after the initial calibration has been performed.

Referring to figure 8.3, K1 is closed and K2 is open when the reactor is shut down. A shutdown signal is then supplied to the reactivity position loops. During this time the reactor should be 3 or 4 percent subcritical. When starting the reactor, K1 opens so that the shutdown bias is removed. The reference signal at the input to amplifier No. 2 forces it to be fully saturated so that it is supplying a maximum withdraw signal. During a previous calibration R* and R_1 have been set so that the drums move to a position corresponding to a definite value of excess reactivity or stable reactor period. The reactor flux rises on a fixed period until the measured flux approaches the zero power level set by ϕ_d and the output of amplifier No. 1. Amplifier No. 1 is always directly connected to amplifier No. 2 and functions as the limited trim control. Flux demand may be temporarily increased so that steady temperature levels are achieved more rapidly. The reactor flux demand would then be reduced to the desired "hold level" at which time the reactor startup is complete.

At some later time the more rapid engine startup is initiated by closing K2 so that the reactor can rise on a shorter period and compensate for propellant reactivity variations. When ϕ_d or measured temperature reaches the desired level, propellant flow is initiated and the turbopump speed is scheduled to provide the desired thrust program.

Power range throttling consists of scheduling turbine speed and reactor power. Turbine speed trim may not be required if only relative rather than exact power plant output is required. Typical response to an acceleration and deceleration schedule in the power range is shown in figure 8.5. From these traces it may be noted that a 10 second acceleration or deceleration response time is readily achieved without a large temperature error. Figure 8.6 shows some typical transients resulting from a near step change in demand schedule. These traces show the time behavior of turbine speed, reactor temperature, reactor power, and reactor discharge pressure. Propellant flow is nearly proportional to this pressure. While the step response changes of figure 8.6 show clearly the system stability they are not typical operations that would be required in most applications. The traces of figure 8.5 are more representative of expected power range maneuvers.

A second system using the same measured parameters is shown in figure 8.4. This system uses a mixed reference during the startup phase of the operation. Amplifier No. 1 has a fixed reference corresponding to a design operating temperature when the setting of P-1, $\alpha = 0$. The output of amplifier No. 1 has proportional control of a smaller amount of reactivity (α 0.7 β) and integral control of the remainder of the reactivity via amplifier No. 3.

During shutdown K1 is closed, K2 is open, and P-1 is set at its maximum value, ($\alpha = 1$). Startup begins by closing K1 which allows complete withdraw of the proportional drum but only limited withdraw of the integrally controlled drums. As before the precalibration setting of R^*/R_1 determines the excess reactivity introduced into the reactor. The reactor rises on a fixed period until ($T_m + \alpha \phi_m$) approaches the fixed reference level T_d. When $\alpha = 1$, T_m is very low so that most of the feedback signal is from the flux measurement.

Flux level and temperature are increased by "fading out" the flux signal, i.e., decreasing the gain setting of potentiometer, P-1. The setting of P-1 is scheduled by a programmer or ganged throttle control which may also control relays K1 and K2. During a reactor startup the steady state setting of P-1 is such that a desired "hold temperature" is achieved. This temperature may be achieved more rapidly if the programmer transiently reduces α to a lower value such that escess flux is introduced temporarily.

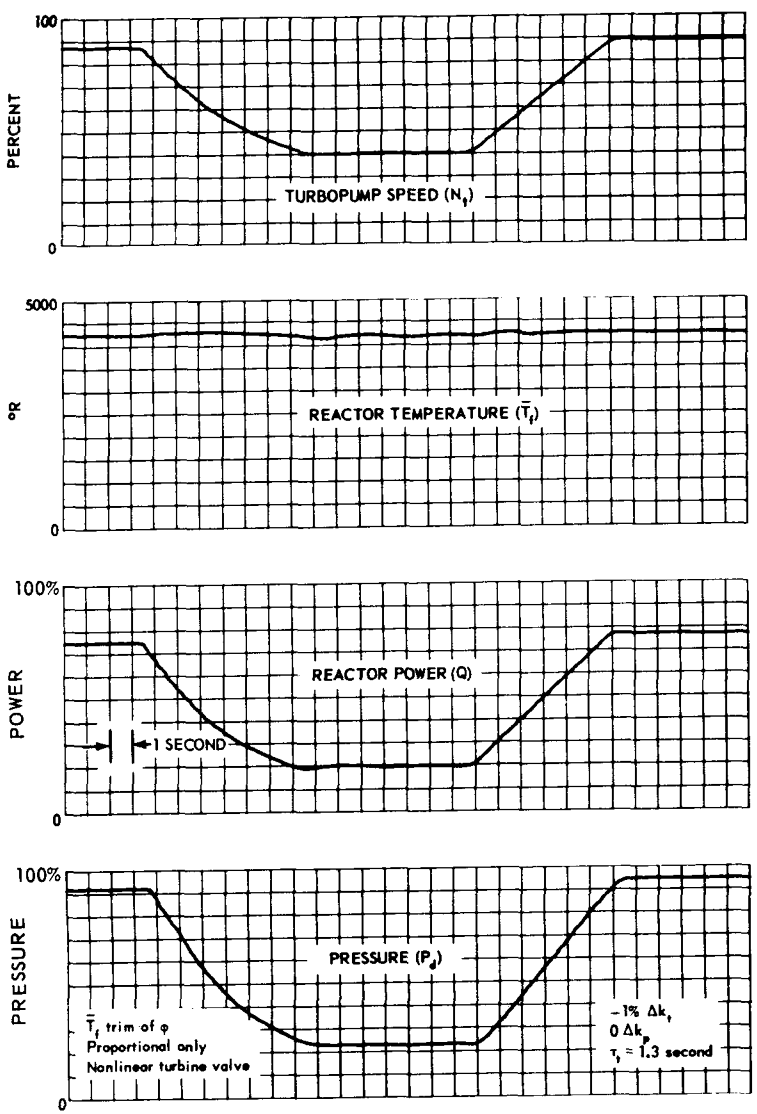


Fig. 8.5 – System No. 1 response to rapid deceleration and acceleration power range maneuvers

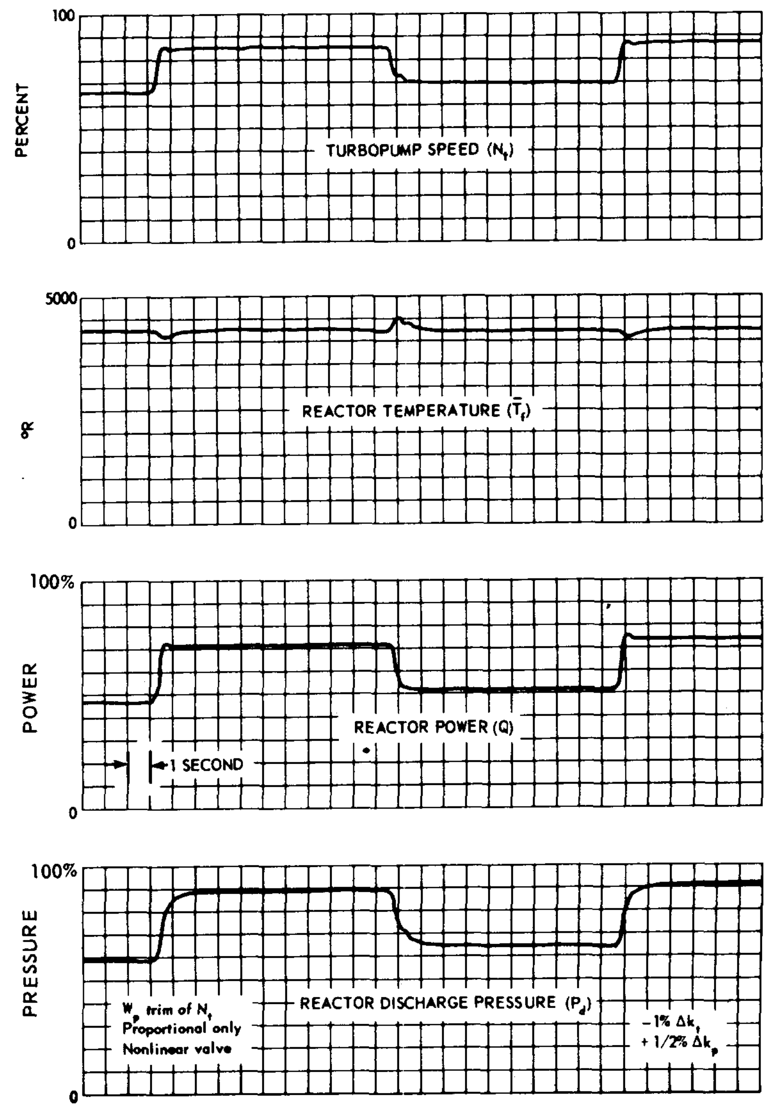


Fig. 8.6 – System No. 1 response to near step changes in demand level

During an engine startup the programmer further reduces α to zero and introduces propellant flow at a rate which the temperature system can follow. Increase in propellant flow lowers the reactor temperature. The temperature error raises the power level. Analog computer traces given in figure 8.7 show that propellant flow may be increased from 20 to 100 percent in less than 10 seconds with a temperature error of about 200°F. The reactor runs cool during the rise to full power and slightly hotter than design temperature during a rapid power reduction. A parabolic or exponential scheduling of the propellant flow distributes the temperature error and reduces the maximum deviation. Slower acceleration and deceleration schedules reduce the temperature error and would be satisfactory for many applications. Figure 8.8 shows that good power range stability exists even for near step changes in demand level.

One other feature that should be noted is that the flux measurement signal is fed into all integrally controlled position loops. As the reactor power rises this input attempts to insert the drums and the integrator must overcome this tendency. The end result is a negative power coefficient of reactivity which provides better stability if the negative temperature coefficient is small or nonexistent. A small negative temperature coefficient, $|\delta k_t| \geqq 0.1\% \ \delta k/1000^{\circ}F$ is highly desirable for safe control of reactors.

8.1 Typical Control System Gain Settings

System No. 1 uses a flux loop with integral control of reactivity. The following gain settings were satisfactory over the expected range of propellant flow and temperature coefficients of reactivity.

Flux Controller $\dfrac{5\% \quad \delta k/\text{minute}}{\% \ \phi \ \text{error}}$

Temperature Trim Control $\dfrac{.04\% \ \phi}{^{\circ}F}$

The proportional trim control may be replaced with a proportional plus integral one with the following gain values:

Proportional gain $\dfrac{.02\% \ \phi}{^{\circ}F}$

Reset gain $\dfrac{.02\% \ \phi/\text{sec}}{^{\circ}F}$

$$\frac{\% \ \varphi}{^{\circ}F} = .02 \left(\frac{S+1}{S} \right)$$

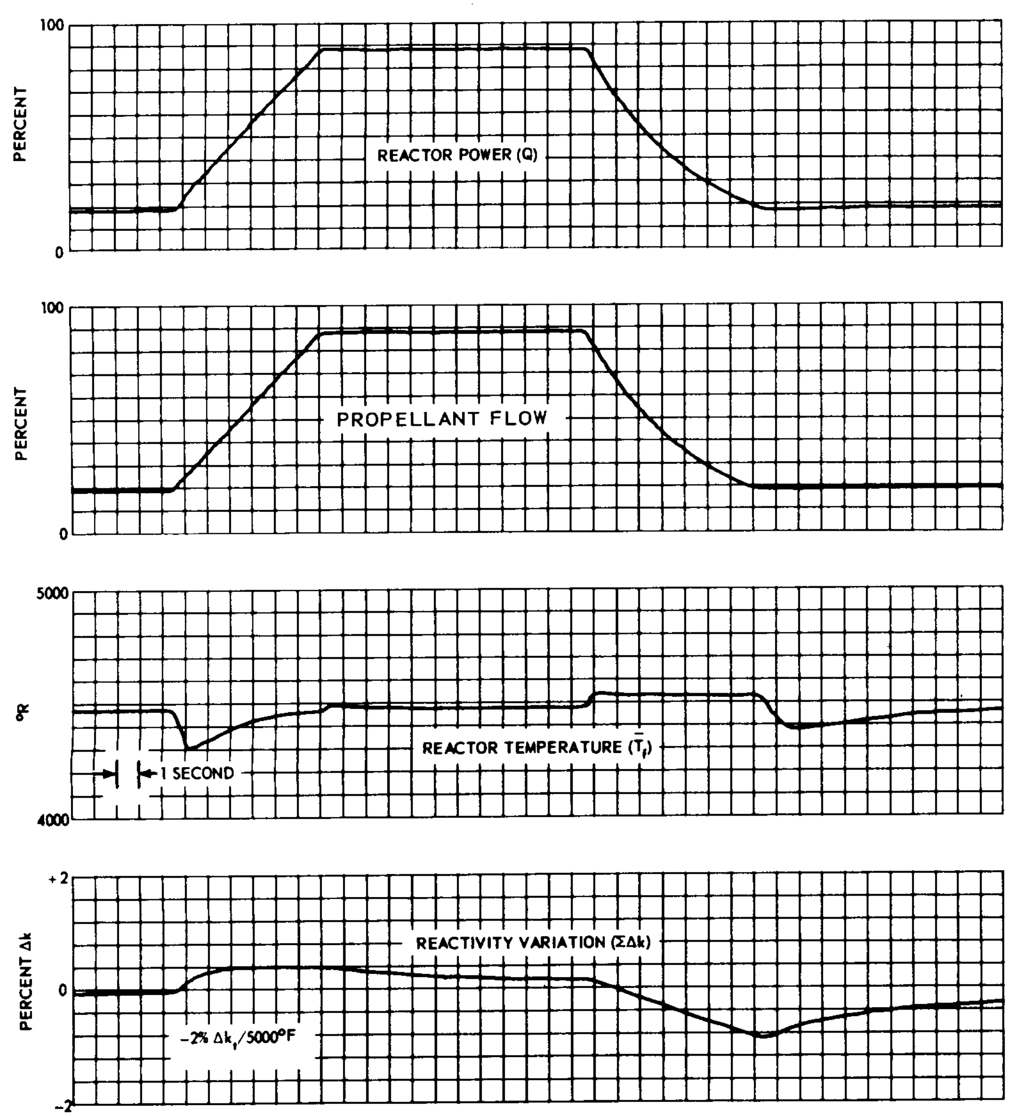


Fig. 8.7 – System No. 2 response to rapid acceleration and deceleration power range maneuvers

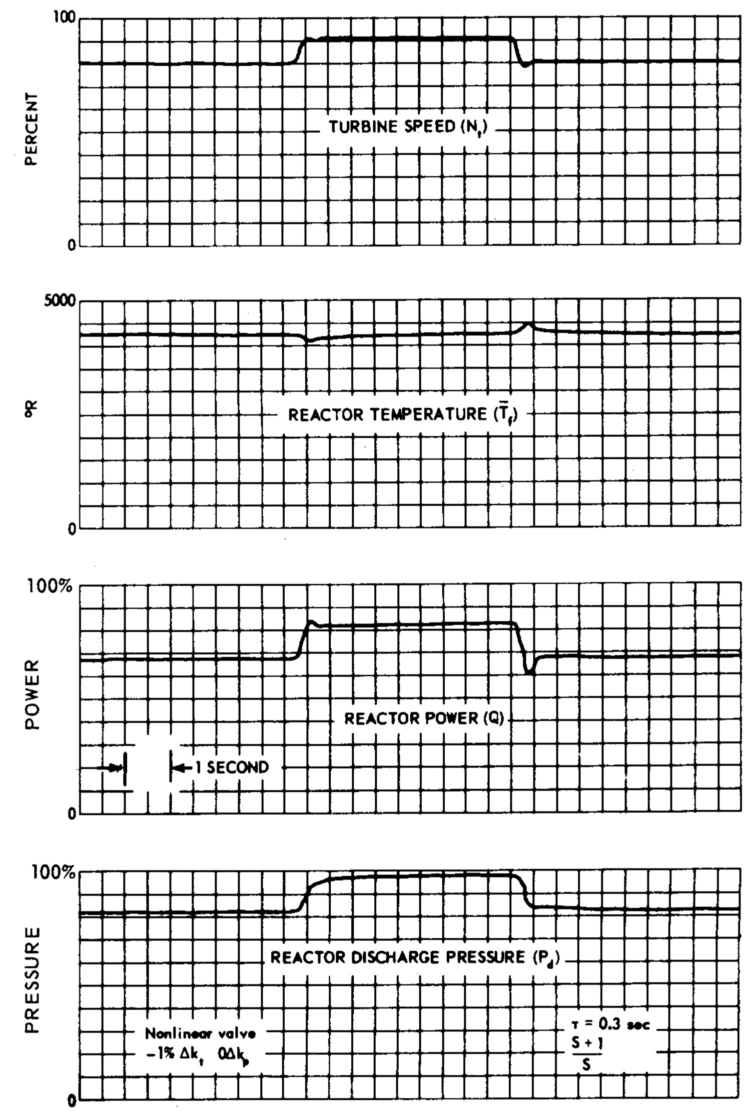


Fig. 8.8 – System No. 2 response to near step changes in demand level

System No. 2 uses proportional plus integral control of reactivity with a flux stabilization signal introduced into the integrally controlled position loops. Gain settings for this system are approximately as given below:

Proportional gain	$.0016\ \%\ \ \delta k/^{o}F$
Integral or reset gain	$.0008$ to $.0016\ \dfrac{\delta k/\sec}{^{o}F}$
Flux stabilization signal	$\geq .01\ \dfrac{\%\ \delta k}{\%\ \phi}$

9. A Summary of Some Possible Control System Arrangements

In section 8.0 it was tacitly assumed that we could obtain a reliable, accurate measurement of temperature. If the measurement is not available we will have to consider other alternatives. There were at least 7 possible measurements suggested in section 4.0 and only 3 or 4 measurements are necessary. This fact suggests that there are many possible arrangements that may be considered for power range operation. There are four basic kinds of power range control systems. Each of these are identified below as well as a number of systems that exemplify each type. Advantages and disadvantages of each system is discussed briefly.

9.1 Type I

This group of systems is based upon scheduling the propellant flow in an arbitrary manner and using the thermodynamic measurements to force the reactor to follow the propellent feed system. Some systems which fall in this category are given below.

9.1.1 Schedule Turbine Speed, N_t, and Reactor Temperature, $\bar{T}_f$

$\bar{T}_f$ error signal controls reactivity and thus reactor power. N_{td}, the speed demand input may have any arbitrary schedule. A closed speed loop forces the turbopump speed to follow the demand.

Advantages

1. Good system response.
2. Reactor runs cool during acceleration because of transient temperature error.
3. During power range operation the exit surface temperature of the reactor is nearly constant and the reactor control system is merely a temperature regulator.

4. Predetermined schedules are not required. The reactor power will be correct to yield the desired temperature for any arbitrary flow schedule unless the flow rate of change is extremely fast.
5. The same reactor temperature measurement may be used for shutdown and aftercooling control of the reactor.
6. System performance does not depend upon maintaining constant nozzle throat dimensions during the operating life of the engine.

Disadvantages

1. Reactor exit surface temperature is high and an accurate sensor with good dynamic response is difficult to develop.
2. A minimum negative temperature coefficient reactivity is required if neutron flux measurements are not used.

9.1.2 Schedule Propellent Flow, W_p, Turbine Speed, N_t, and Reactor Temperature $\bar{T}_f$

This system is similar to the one above except that propellent flow is measured then compared to a scheduled demand, W_{pd}. The error signal is used to trim a scheduled turbine speed.

Advantages

1, 2, 3, 4, 5, and 6 of 9.1.1.

7. Thrust can be closely controlled if desired. For many applications this would be no advantage. Velocity increment is computed or measured and this can be used to terminate any arbitrary thrust program.

Disadvantages

1. Reactor temperature is a difficult measurement.
2. Another somewhat difficult measurement has been added, i.e., the mass flow of liquid hydrogen.

9.1.3 Schedule Propellent Flow, W_p, and Reactor Temperature, $\bar{T}_f$

Turbine speed is not scheduled. Turbine speed demand is generated by proportional plus integral control of propellent flow.

Advantages

2. through 7. of 9.1.2.
8. Scheduling of N_t not required.

Disadvantages

1. and 2. of 9.1.2.
3. Dynamic response is not as good as the system of 9.1.2. (Revealed from analog computer studies.)

9.1.4 Schedule Reactor Discharge Pressure, P_c, Turbine Speed, N_t, and Reactor Temperature, $\bar{T}_f$

This system is like 9.1.2 except chamber pressure, P_c instead of propellent flow, is used to trim a scheduled turbine speed, N_t.

Advantages

1, 2, 3, 4, and 5 of 9.1.1.
6. Chamber pressure is an accurate measure of thrust. Thrust can be closely controlled.

Disadvantages

1. Reactor temperature is a difficult measurement.
2. An additional measurement is required (P_c).

9.1.5 Comments

Discharge gas temperature instead of core temperature may be used in the above systems but such a measurement is useful only in the power range. Other systems like 9.1.3 using measured chamber pressure instead of flow also have the disadvantage of undesirable dynamic response. System 9.1.1 appears to be the best system in this group assuming that accurate thrust control is not required. If this latter requirement exists system 9.1.4 would be selected as the first choice.

9.2 Type II

This group of systems is the reverse of those considered in 9.1. This type is based upon scheduling reactor flux. They use thermodynamic measurements to force the propellent feed system to follow the reactor. Some typical systems of this group are given below.

9.2.1 Schedule Reactor Flux, ϕ, Reactor Temperature, $\bar{T}_f$ -

Proportional plus integral control of T_f is used to control turbine speed. A speed loop is required to maintain satisfactory stability. The integral of temperature error is the steady state demand input to the speed loop.

Advantages

1. Fairly good response.
2. During power range operation the exit surface temperature of the reactor is nearly constant. The propellent control system is then merely a temperature regulator.
3. Predetermined flux schedules are not required. Propellent flow will be correct to provide the demand temperature level assuming that the propellent feed system is fast enough to follow the reactor flux schedule.
4. The same temperature measurement may be used for shutdown and aftercool control.

Disadvantages

1. Reactor temperature is a difficult measurement.
2. Dynamic accuracy is not as good as system 9.1.1.
3. Reactor tends to run hot during acceleration.

9.2.2 Schedule Reactor Flux, ϕ, Reactor Temperature, and Turbine Speed, N_t -

This system is like 9.2.1 except temperature is used as a trim control. Turbine speed is scheduled to provide an approximate propellent flow. The temperature controller is then required to cover a limited range only.

Advantages

1, 2, 3, and 4 of 9.2.1.
5. Dynamic accuracy and stability is better than system 9.2.1.

Disadvantages

1. Reactor temperature is difficult to measure.
2. Speed schedule must be set to compensate for higher reactor temperature that would normally exist during acceleration.

9.2.3 Schedule Reactor Flux, ϕ, Turbine Speed, N_t, and Chamber Pressure, P_c -

This system uses reactor discharge pressure to trim propellent flow instead of temperature. Otherwise it is similar to system 9.2.2.

Advantages

1. Good stability.
2. Thrust can be controlled more accurately than with systems 9.2.1 and 9.2.2.
3. A difficult high temperature measurement is not required.

Disadvantages

1. Schedules for ϕ, N_t, and P_c must be determined accurately.
2. Steady state performance is dependent upon how well ϕ actually represents reactor power, (BTU/sec).
3. A lower temperature measurement is still required for aftercool control.
4. Nozzle throat dimensions must not change appreciably during the operating life of the engine.

9.2.4 Comments

There are other systems which use propellent flow, W_p, T_f, and ϕ that fall in this group. However, computer studies indicated that they show no real advantage to justify the additional complexity. Systems 9.2.2 or 9.2.3 show the greatest potential. Systems 9.2.2 would be selected if a good high temperature sensor could be developed. System 9.2.3 avoids the high temperature measurement but requires good correlation between reactor flux and reactor power.

9.3 Type III

This group of systems is a combination of the first two types. Both reactor power and turbine speed are scheduled. Thermodynamic parameters are used to trim both the reactor and propellent feed system. Systems of this type are given below.

9.3.1 Schedule Propellent Flow, W_p, Turbine Speed, N_t, Reactor Flux, ϕ, and Chamber Pressure, P_c –

Propellent flow is used to trim turbine speed and pressure is used to trim reactor power.

For a given weight flow of propellant the reactor must have the correct power to establish the pressure demanded at the reactor discharge. Pressure in this system is an indirect measure of reactor discharge gas temperature. If the nozzle throat dimensions do not change $P_c = f_1 (W_p, \phi)$ and $T_c = f_2 (W_p, \phi)$. For a given W_p value for P_c exists such that T_c does not exceed design value.

Advantages

1. Good stability with fairly small dynamic error.
2. High temperature sensors are not required.
3. Thrust may be accurately controlled if desired.

Disadvantages

1. Schedule for four variables must be accurately determined.
2. System depends upon nozzle throat dimensions not changing much during the operating life of the engine.
3. A lower temperature measurement is still required for aftercool control.

9.3.2 Schedule Reactor Flux, ϕ, Turbine Speed, N_t, Reactor Temperature, $\overline{T}_f$ and Chamber Pressure, P_c

Pressure is used to trim turbine speed while reactor temperature is used to trim flux.

Advantages

1. Good stability with small dynamic error.
2. Thrust may be accurately controlled if desired.
3. The same reactor temperature may be used for aftercool control.
4. System performance does not depend upon maintaining constant nozzle throat dimensions during the operating life of the engine.

Disadvantages

1. Schedules for variables are required but they need not be as accurately determined as in system 9.3.1.
2. Reactor temperature is high and an accurate sensor with good dynamic response is difficult to achieve.

9.3.3 Schedule Reactor Flux, ϕ, Turbine Speed, N_t, and Reactor Temperature, $\overline{T}_f$

Use temperature to trim reactor flux and operate a proportional δ k drum. This transient temperature control of reactivity provides better stability with smaller dynamic error.

Advantages

1\. 3, and 4 of system 9.3.2.

5. Analog computer studies of this system indicate that it is better than most other systems.

Disadvantages

1. Reactor exit surface temperature is a difficult measurement.

9.3.4 Comments

There are other less promising systems that could be listed in this group. As in the other group of systems, reactor discharge gas temperature may be substituted for exit surface temperature but this measurement would be useful only in the power range. System 9.3.3 appears to be the best system of this group unless accurate control of thrust is required. If temperature cannot be measured satisfactorily, system 9.3.1 looks good.

9.4 Type IV

There are a few systems which make use of very indirect measurements to achieve reactor control. To use such systems successfully, the characteristics of the reactor and its interdependence upon engine parameters must be known accurately. If these characteristics change with operating time then the control system calibration must be changed to correspond. Drum position is used as an indication of temperature assuming that a sufficiently large negative temperature coefficient of reactivity exists. The propellant reactivity must also be known. A few examples are given below.

9.4.1 Schedule Turbine Speed, N_t, Propellant Flow, W_p, and Reactivity Drum Position. Use W_p to Trim Control N_t.

Theoretically there is a drum position which corresponds to the correct temperature. This is similar to startup system No. 3 of Section 5.3. It has an inherent temperature loop similar to System 9.1.1 if a negative temperature coefficient exists.

Advantages

1. High temperature measurement is not required.
2. Thrust could be fairly well controlled.
3. Startup control is simplified.
4. Reactor runs cool during acceleration.

Disadvantages

1. Drum position to establish the correct reactor temperature must be accurately known and must not shift with operating time. Drum position calibration depends on reactivity due to change in temperature and propellant flow.
2. Reactor temperature excursions are large during acceleration and deceleration maneuvers even when a negative temperature coefficient of $-10\%/5000^{\circ}F$ exists.
3. Space simulators would be required to do the calibration work.
4. Accurate propellant flow is not an easy measurement.
5. A lower temperature measurement is also required for aftercool control.

9.4.2 Schedule Turbine Speed, N_t, Chamber Pressure, P_c, and Drum Position Use P_c to trim N_t

Advantages

1, 2, 3, and 4 of system 9.4.1.

Disadvantages

1, 2, 3, 4, and 5 of system 9.4.1.

9.4.3 Comments

These systems are theoretically possible but accurate calibration which is free from drift appears unlikely. Certainly these systems cannot be counted on until a great deal of operating experience is attained with one of the other types of control systems.

10. Engine Control Without Using Temperature Measurements

If reactor or gas discharge temperature measurements cannot be measured accurately and reliably, we must resort to alternate arrangements. System 9.3.1 of the preceding section is one possible approach. As an example, we now consider this system for use with a reactor generating 300 M.W. of power and delivering 1500 lbs of thrust. We assume that propellant flow can be measured sufficiently accurate ($\pm$ 1%) but the reactor power cannot be determined accurately enough ($\pm$ 5 to 10%).

For a given propellant flow, W_p, there should be a predetermined reactor discharge pressure, P_c, if the reactor is delivering the correct power to produce design temperatures. Pressure may then be measured and compared with a scheduled demand as shown in Figure 10.1. The resulting error signal can then be used to correct the scheduled reactor power level. The transfer function diagram of Figure 10.1 is based upon a refractory metal reactor with relatively low heat capacity and a fairly high reactor discharge pressure.

The simplified transfer functions representing these controllers are given by equations 10.1 and 10.2 below.

$$G_1 (S) = \frac{0.125}{(0.5S + 1)} \quad \frac{\% \phi}{\text{psi}} \tag{10.1}$$

The propellant flow control transfer function is given by equation 10.2.

$$G_2 (S) = \frac{10}{0.5S + 1} \quad \frac{\% N}{\#/\text{sec}} \tag{10.2}$$

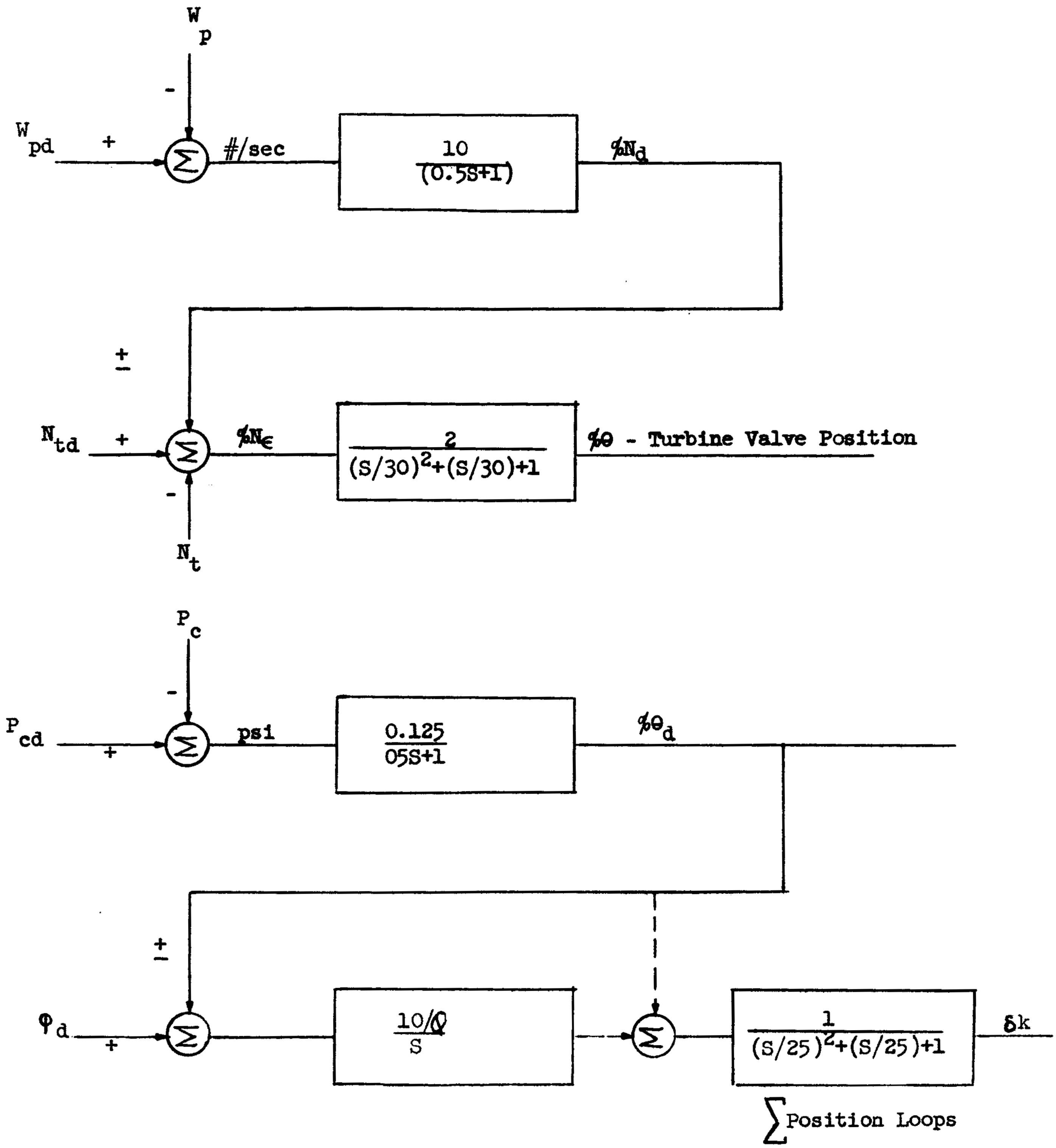


FIGURE 10.1 - TRANSFER FUNCTION DIAGRAM OF THE PRESSURE AND PROPELLENT FLOW CONTROL

Analog computer studies show that the stability of this control system is good for a wide range of temperature and propellant coefficients of reactivity. Figures 10.2 and 10.3 show some typical engine response recordings to ramp changes in demand. The temperature error is greater during a rise in power than during a fall in power. Reactor discharge pressure is maintained at the expense of increase in fuel element temperature during the power rise. The temperature increase is much less for smaller ramp changes and for lower ramp rates. This transient occurs for several seconds and can be compensated for when designing the schedules for the programmer. A transient time delay may be introduced into the pressure demand schedule to accomplish the same thing.

From equations 10.1 and 10.2 we note that no integration has been included so that a steady state error between demanded pressure and flow and actual measured values exist. If a proportional plus integral control of the form given by equation 10.3 is used the steady state error is zeroed out.

$$G(S) = \frac{k(\tau_1 S + 1)}{S(\tau_2 S + 1)} \qquad \tau_1 > \tau_2 \qquad (10.3)$$

However, a proportional plus integral controller is more complex and the increase in accuracy may not justify the more elaborate control system.

Most of the operating time will be at full thrust level and from Figure 10.3 we note that the pressure controller operates best in this region. For this reason it may be desirable to leave the pressure trim control inactivated until the pressure approaches the full thrust level. The pressure controller can then be replaced with a mechanical pressure regulator which is activated only in the upper power range. The specific impulse and reactor temperature may then be made lower during the rise to power but would be maintained correct when full thrust is achieved. This approach would utilize the propellant efficiently and allow the use of mechanical pressure regulator which would not have to be scheduled. Automatic means of activation and deactivation can be designed directly into the regulator without the use of electrical measurements and switching.

11. Engine Shutdown and Aftercooling the Reactor

Heat generated by a reactor is the result of the fissioning processes. Most of the heat is released immediately but a small part of it is generated by the fission products after a substantial delay time. During normal reactor operation the concentration of fission products in their excited state is building up. The long life excited state

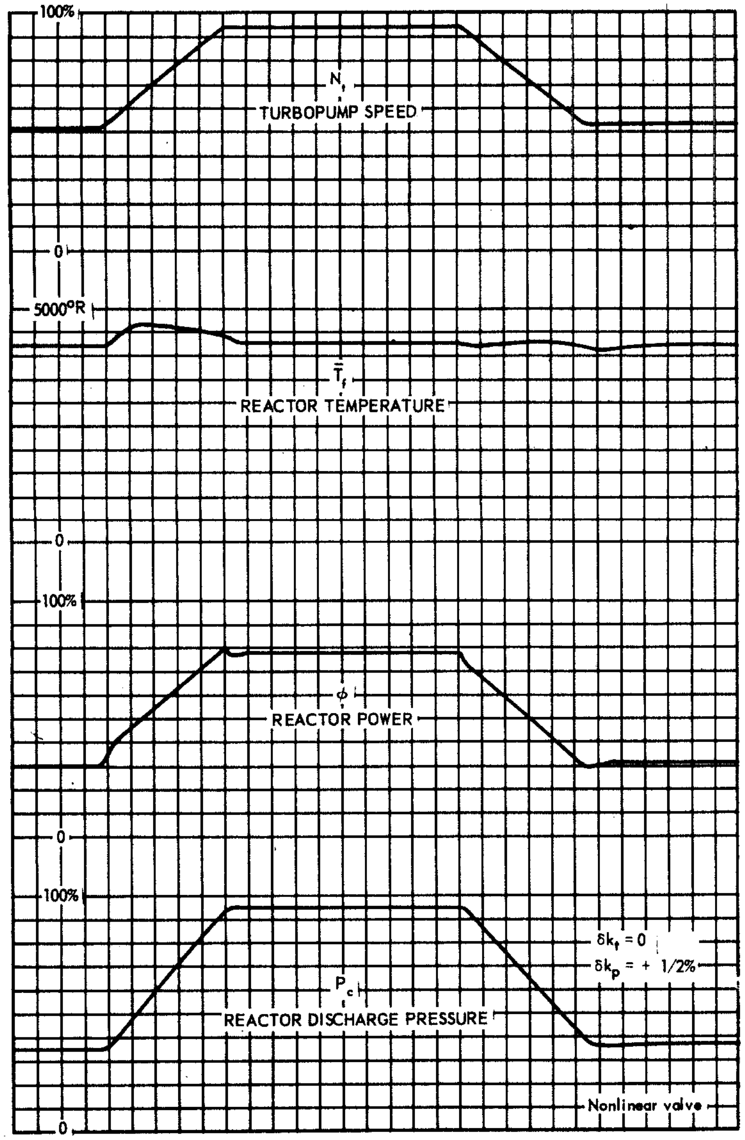


Fig. 10.2 – Engine response traces to ramp changes in demand

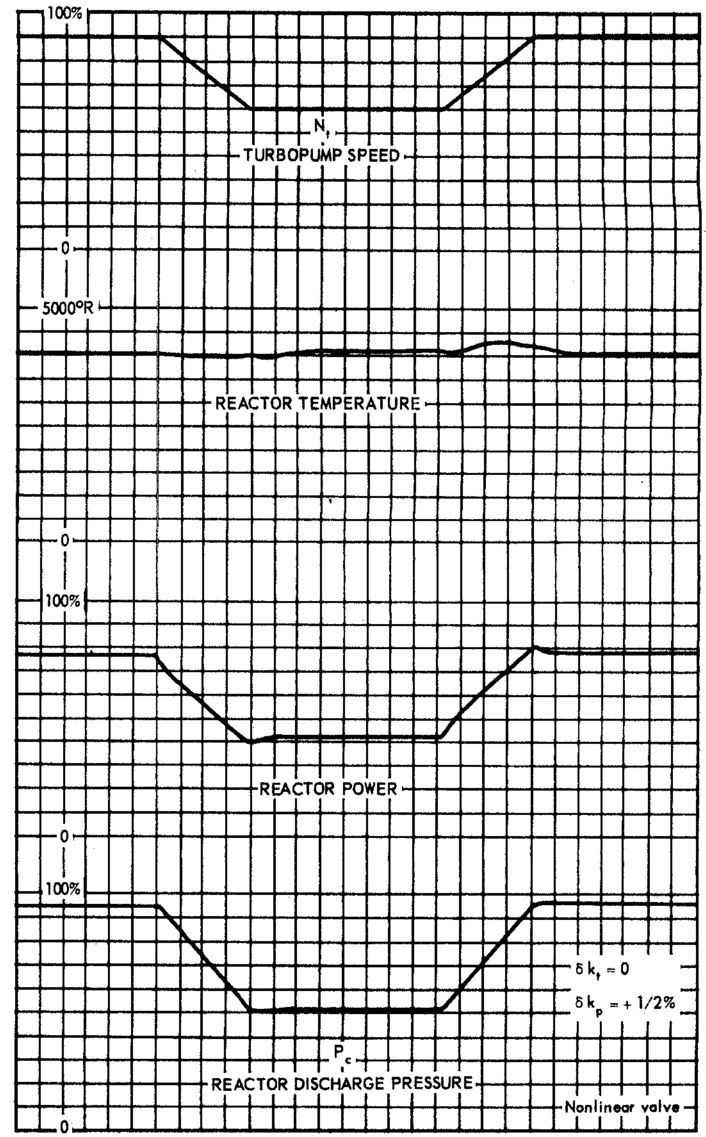


Fig. 10.3 – Engine response traces to ramp changes in demand

products buildup to their equilibrium level slowly and the short life ones reach their equilibrium state more rapidly. Some of the short life products include those that emit the delayed neutrons. When a shutdown occurs the delayed neutron heat source decays rapidly (100 seconds) and after a few minutes the longer life fission products heating predominates.

Fission products consist of a large number of radioisotopes each specie having a different characteristic decay constant. Time behavior of each isotope is represented by simple first order differential equations, one for each decay process.

(1) $$\frac{dNi}{dt} = -\sum_{j} \lambda ij\ Ni + \gamma i\ \Sigma f\ \phi$$ Typical equation for the ith radioisotope.

(2) $$Pf = \sum_{ij} k_{ij}\ \lambda_{ij}\ Ni \quad \text{BTU/sec}$$

Ni = Concentration of the ith isotope

λ_{ij} = Decay constant of the jth process, ith isotope

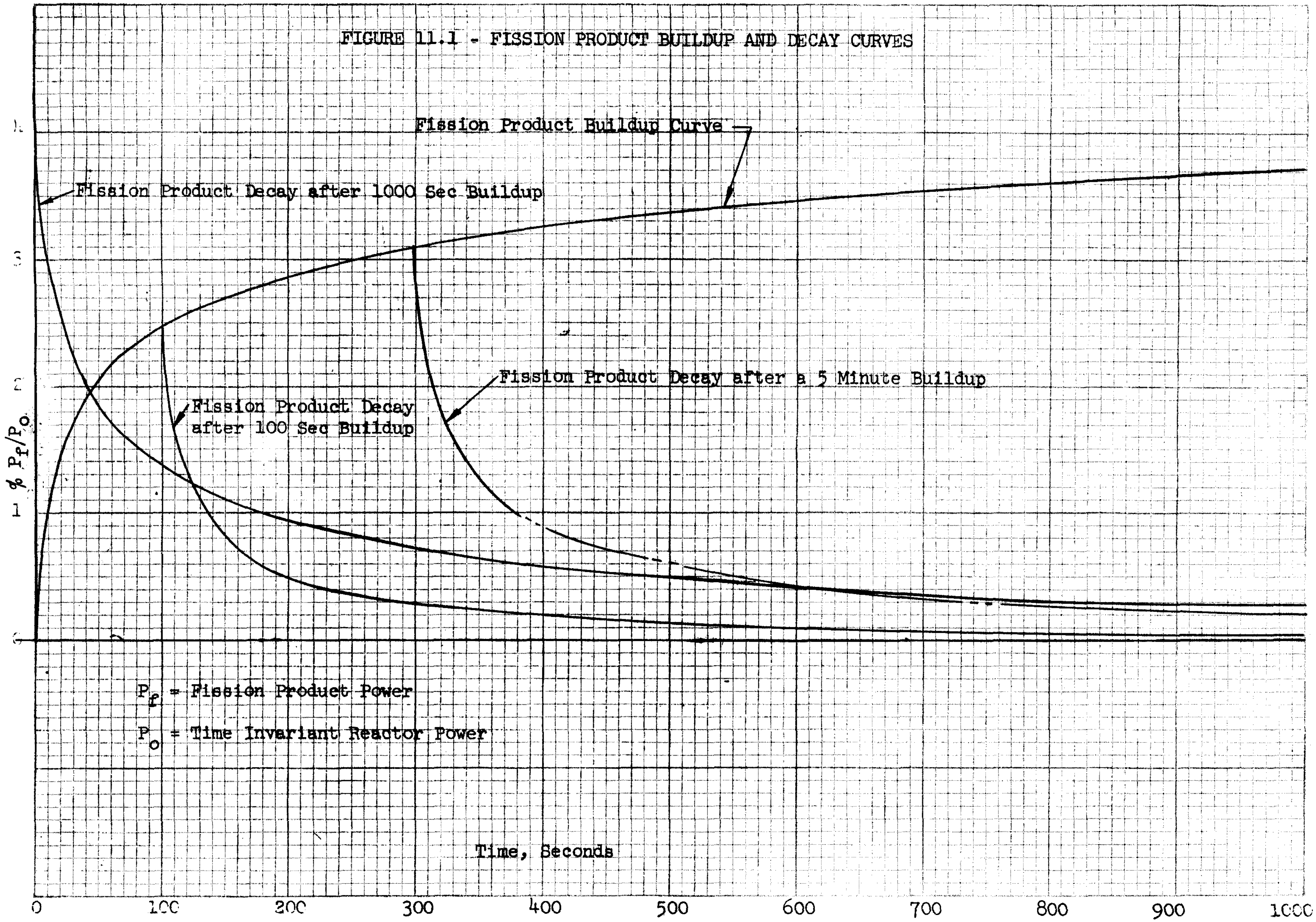
γ_i = Probability of generating the ith isotope when fission occurs.

k_{ij} = Proportionality weighting factor which depends upon the contribution of heating from the processes involved.

There are hundreds of decay processes contributing to the total fission product heating represented by equations (1) and (2). Figure 11.1 shows the buildup of the fission product power for a U^{235} fueled reactor. This figure also shows several fission product power decay curves after the reactor has been shutdown. The reactor is assumed to have been operating at constant power, P_o, for the time given on the abscissa for the buildup curve. The shutdown decay curves start at a point given on the buildup curve except for the 1000 second buildup case which has been translated back to zero time to show the decay portion for the following 1000 seconds. From these curves we note that the longer life isotopes generate a small amount of power for a substantial time after shutdown.

When shutting down a reactor, the propellant flow and reactor power could theoretically be scheduled to maintain any desired reactor temperature-time relationship. It is always necessary that the reactor core temperature does not exceed some upper design temperature and sometimes it is desirable to maintain the temperature above a fixed lower limit. ~~Figures 11.2 through 11.6 show some temperature-time relationships for different propellant-power schedules and a reactor with a fairly low heat capacity.~~

FIGURE 11.1 - FISSION PRODUCT BUILDUP AND DECAY CURVES



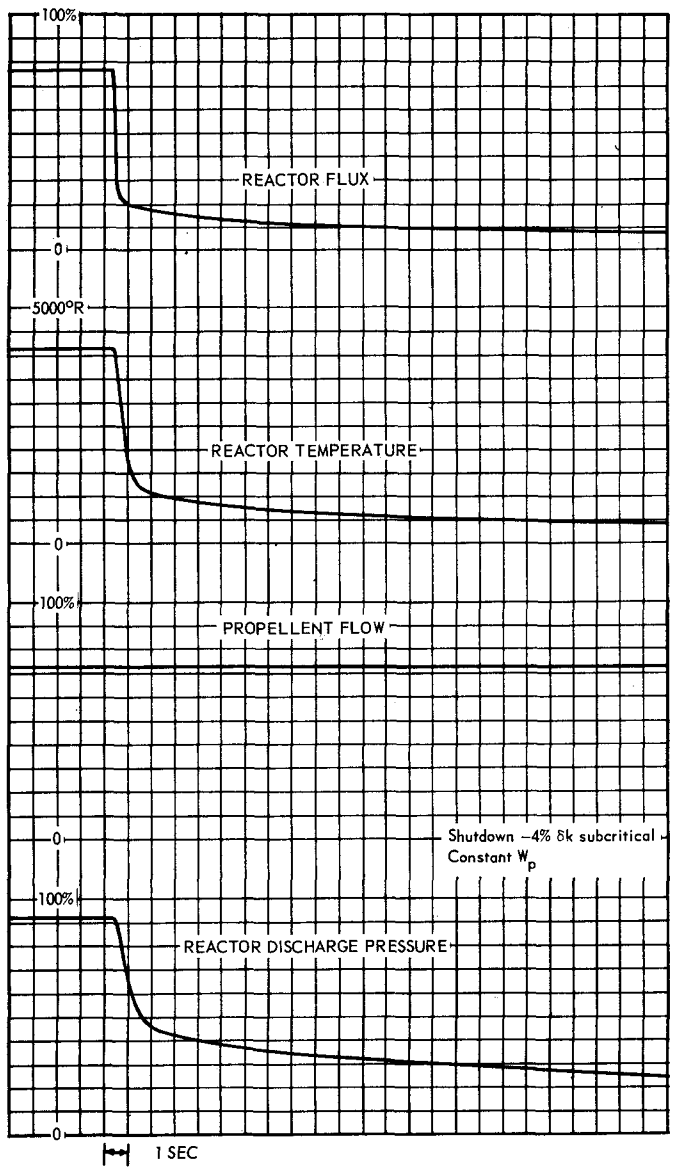


Fig. 11.2 – Reactor response to a scram after a 15 minute thrust run at full power

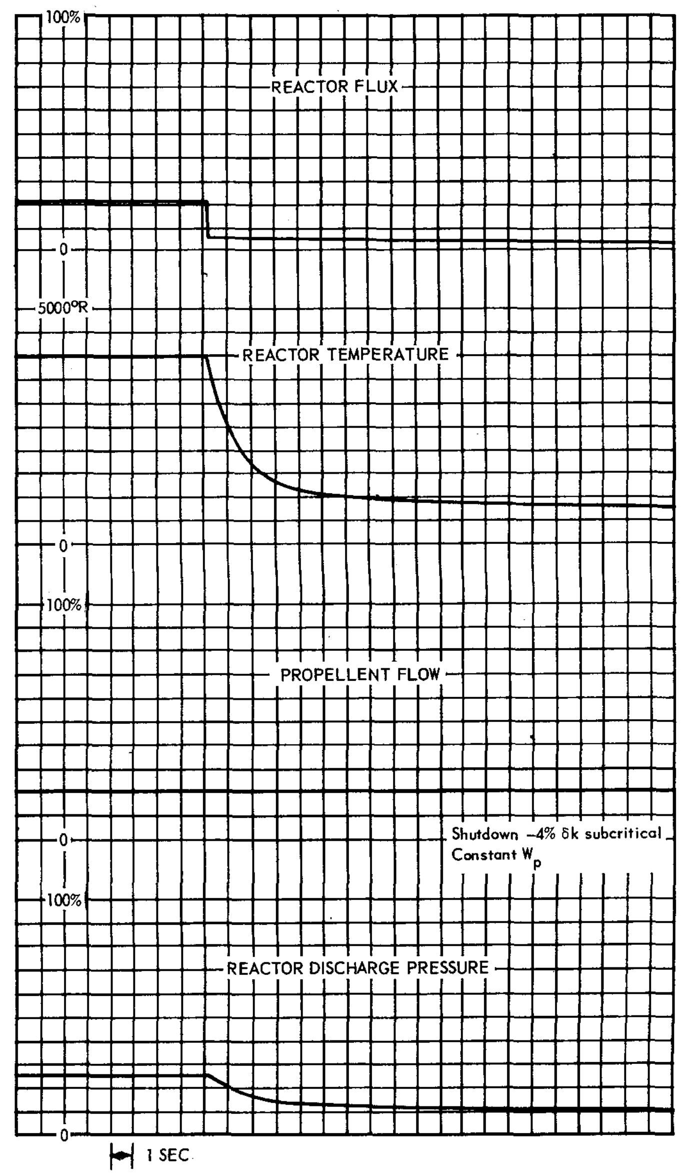


Fig. 11.3 – Reactor response to a scram from a 20 percent thrust level

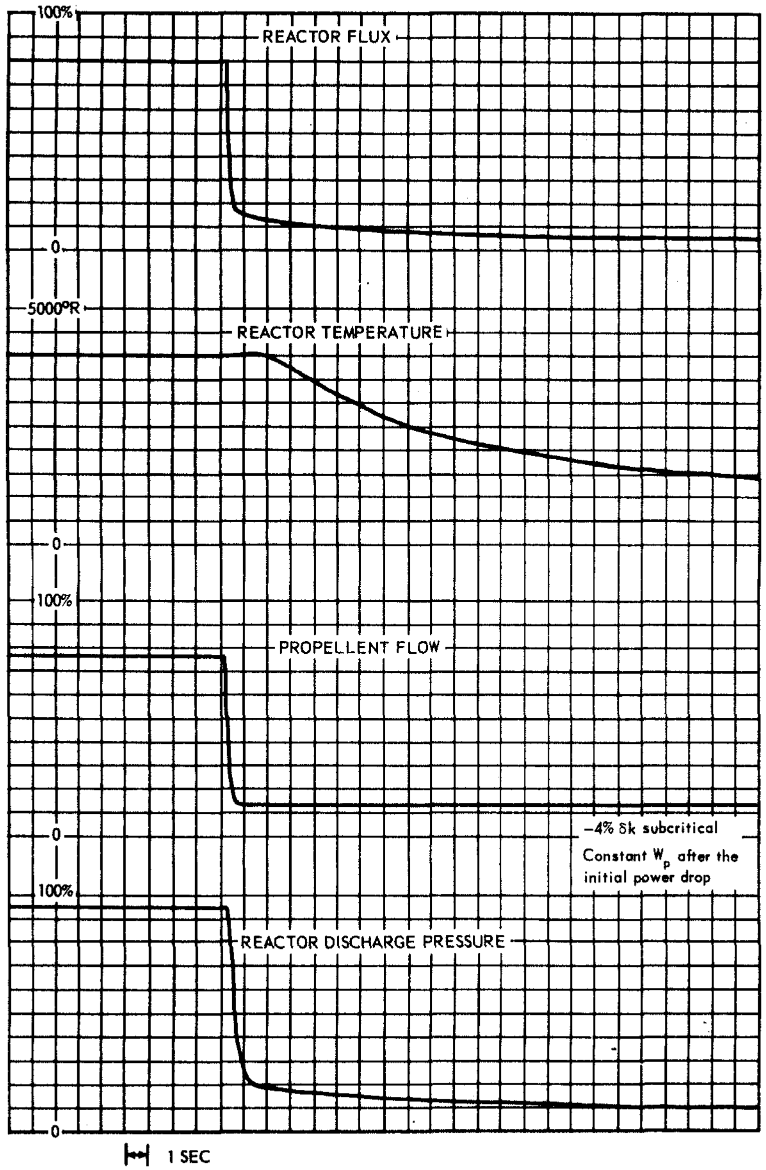


Fig. 11.4 – Reactor temperature response to matched flow and power during the initial shutdown

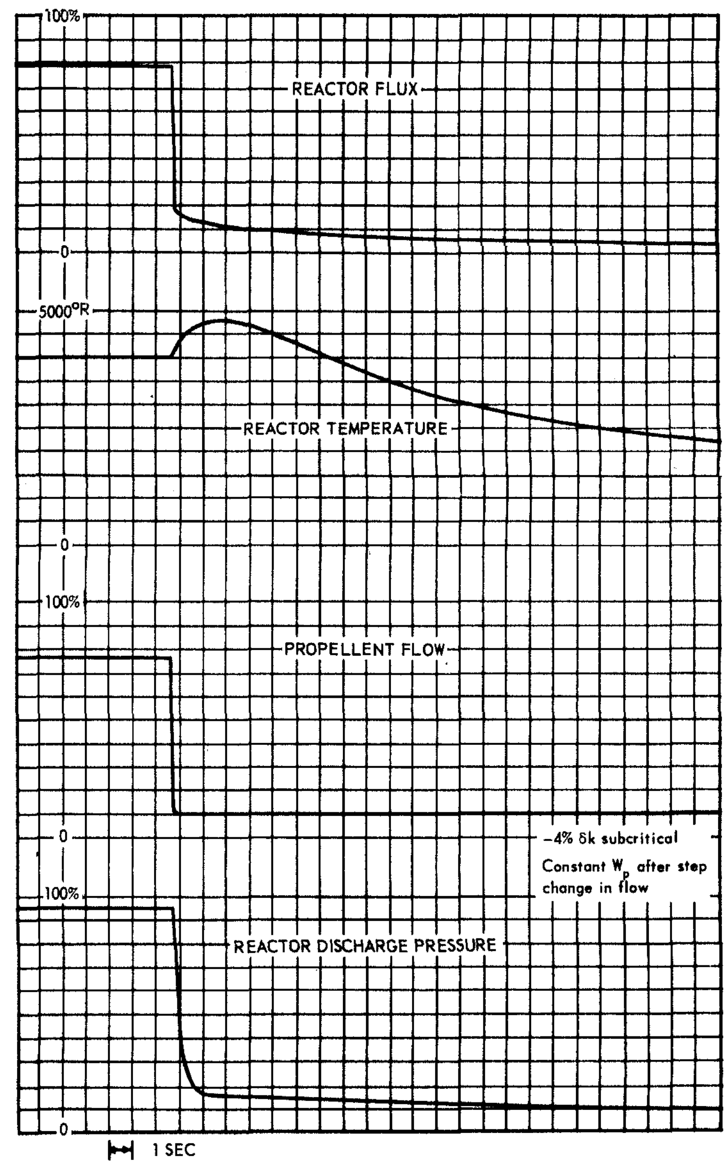


Fig. 11.5 – Reactor temperature response to unmatched flow and power during a shutdown

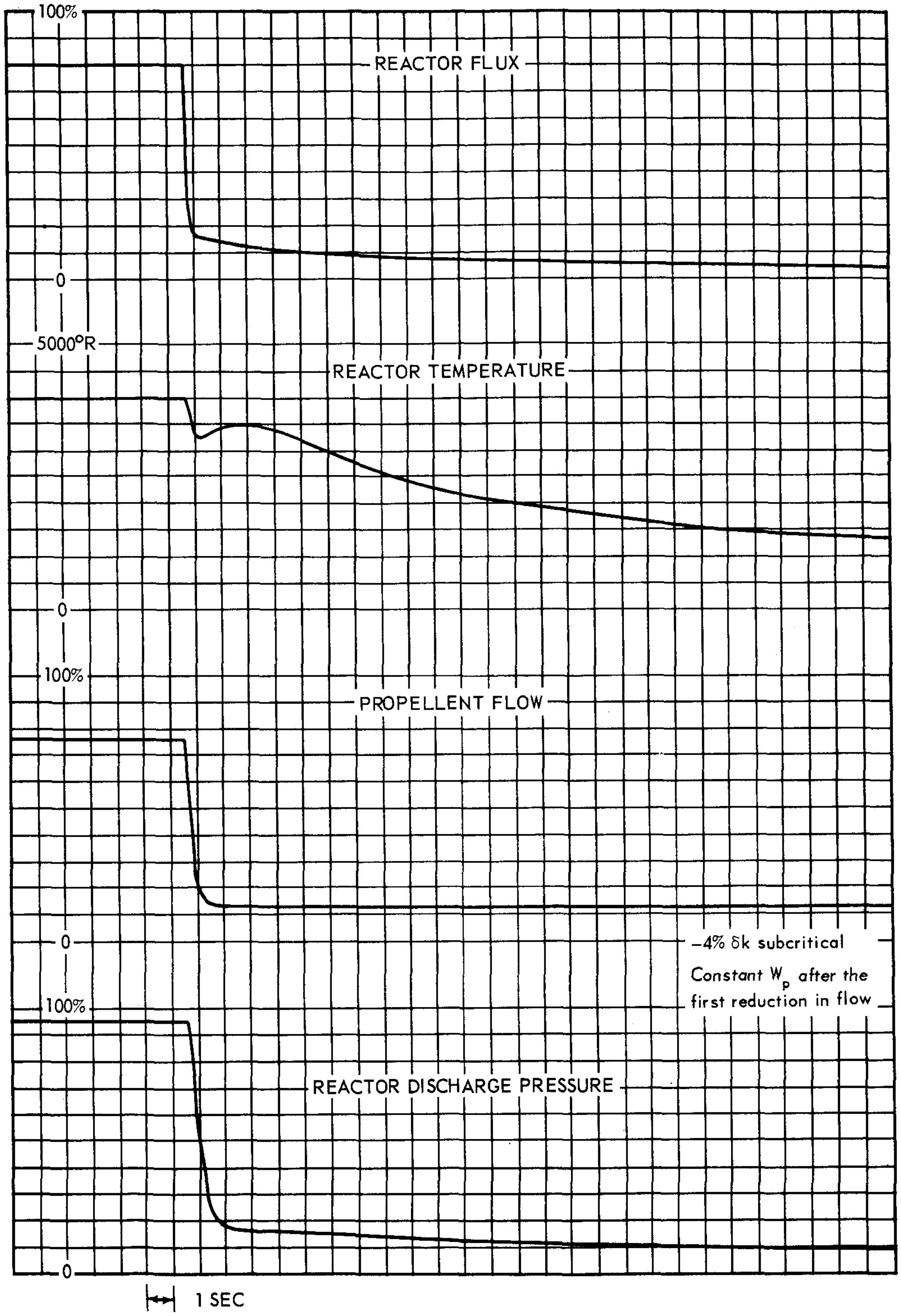


Fig. 11.6 – Reactor temperature response to a slight mismatch in propellent flow and power during a shutdown

Figures 11.2 through 11.6 show some temperature-time relationships for different propellant-power schedules and a reactor with a fairly low heat capacity. Figure 11.2 shows response traces in which the reactor was suddenly shutdown with full propellant flow. The temperature falls at extremely fast rate. Figure 11.3 shows that the temperature rate is reduced if the shutdown were initiated at 20% of full power. A scram or rapid shutdown from full thrust should be avoided if possible, but if it is necessary, the propellant flow should be scheduled to approximately follow the reactor power.

Figure 11.4 shows some response traces when the propellant flow is scheduled to follow the reactor power during the initial transient only. After the initial transient, the propellant is maintained at 20% flow. The temperature gradually falls off at a slow rate in response to the fission product and delayed neutron decay. Figure 11.5 represents a rapid shutdown in which the propellant flow is reduced to a value lower than the corresponding reactor power. The reactor is made -4% δk subcritical and the reactor power falls to 20% of its initial level. The propellant flow is cut to 12% so that the reactor temperature rises temporarily until the fission product and delayed neutron power decays to the 12% level. Figure 11.6 shows a case where the propellant flow schedule is not quite matched to the reactor power during a rapid shutdown from full power. There is a quick but small initial temperature drop followed by a slight rise before a gradual fall off occurs. Over a 10 second averaging time, the temperature rate of change is less than that of Figure 11.4.

To summarize, we conclude that during a rapid shutdown the propellant flow should be scheduled to approximately follow the reactor power until the aftercooling system takes control. A temperature controlled reactor would automatically perform the operation satisfactorily if the turbopump could be decelerated rapidly or its bypass surge valve opened quickly. There will always be some inertia in a propellant feed system so that an initial fall in temperature will occur if a fast scram from full power is permitted. A normal shutdown and the phasing into the aftercool control is not difficult if the reactor is temperature controlled.

11.1 Aftercooling the Reactor

During the aftercooling period the reactor power is no longer controllable. Reactor temperatures must be controlled by modulating the propellant flow either on a continuous or discontinuous basis.

Continuous aftercooling flow systems require diminishing flow after a scram or shutdown. A small flow must be supplied for a half hour or more after shutdown, depending upon how much power can be radiated into space without exceeding the design temperature of any part in the engine. Furthermore, the flow through the reactor may become laminar at lower flow levels possibly resulting in an unstable flow pattern.

A discontinuous system avoids laminar flow by pulse cooling the reactor. If the propellant is intermittently turned on and off, the reactor temperature will rise and fall. If the sequence of operations is properly timed, the reactor temperature will vary between an upper and lower temperature limit.

Aftercooling pulsation may be controlled by direct or indirect temperature measurements or computed from the past operating history of the reactor. The latter method does not appear attractive because the time integral of power alone is not sufficient to make this computation. A large number of variables affect the aftercool valve timing, some of which are given below.

1. Fission Product Power

   Depends upon the past reactor operating power levels and hence the thrust program. This power cannot be accurately determined.

2. Delayed Neutron Power

   Another part of the afterheat power is generated by delayed neutrons which exist a few minutes after a shutdown. This power is more predictable than fission product power if the shutdown reactivity is known. Temperature and propellant coefficients of reactivity and fission product poisons make it difficult to predict how far subcritical the reactor will be after a shutdown.

3. Thermal Capacity

   The heat capacity of the core as well as the above sources of afterheat determine the pulse rate and pulse area. The thermal heat capacity is a function of the reactor temperature. The relationship is not predictable to a high degree of accuracy.

4. Reactor Core Temperature

   Propellant pulse timing is also determined by the high and low temperature limits of the cycle. On a short time basis there is some degree of freedom to absorb some of the uncertainties in the above variables. However, the average core temperature will drift up or down on a long time basis unless exact pulse width and rate can be established.

5. Radiation Cooling During and Following the Aftercool Period

   Radiation power can never be accurately predicted and it does influence the pulse sequence timing after 15 minutes of shutdown. Aftercooling operations can be terminated only when the radiated power is sufficient to remove the afterheat power without exceeding allowable design temperatures.

Figures 11.7 and 11.8 show how the reactor behaves during the aftercooling time using a pulsed cooling system. The reactor core is cycled between fixed temperature limits. A direct or indirect temperature measurement of the upper temperature limit opens a propellant valve while a lower temperature measurement closed the propellant valve. In practice this may be accomplished with a single temperature controller shown in Figure 11.9. This may be an integral part of some of the temperature systems of Section 9.

The output of the temperature error amplifier is rectified and used to control a relay. When the temperature error is low the relay is de-energized and the propellant valve is turned on. Reactor temperature is then reduced and the error is increased until the relay is energized, at which time the propellant valve is turned off.

An on-off temperature control of this type is a form of relaxation oscillator. A nearly saw-tooth temperature wave-form exists as shown by Figures 11.7 and 11.8. These figures show the measured temperature response as well as that of the core for temperature sensors with a 1.2 and 5 second time constant. The temperature signal from the shorter time constant follows the core temperature fairly well during the rise but cannot follow the rapid fall in temperature produced by propellant flow.

The longer time constant of 5 seconds may be associated with an indirect temperature measurement of the core. As an example a thermocouple may be imbedded in the reflector. The reflector temperature may be proportional to the core temperature except for its larger heat capacity. Figure 11.8 shows the temperature signal resulting from a 5 second sensor lag. The average temperature that the sensor produces follows the average temperature of the core but the instantaneous temperature readings differ greatly.

There is a great deal of contrast between a continuous temperature controller and an on-off temperature controller. Increased sensor time lag tends to make a continuous controller less stable unless the gain is reduced. Exactly the opposite is true for this on-off temperature control which in one sense of the word is always unstable in that it is in continuous oscillation. To maintain a fixed upper and lower temperature limit, the gain must be greater for the 5 seconds time constant case. Figure 11.7 shows that the difference between the pickup and drop out of the relay for $\tau = 1.2$ seconds is 400°F of measured temperature, while Figure 11.8 shows that for $\tau = 5$ seconds this differential is only 100°F. The gain of the relay amplifier is roughly proportional to the temperature sensor time constant.

Aftercooling propellant consumption and the pulse rate are decreased if the thrust is reduced to 15 or 20% of full power about one minute before completing the shutdown. Figure 11.10 shows this trend for a small nuclear rocket. The percentage of savings is greater for short thrust runs than for long thrust runs.

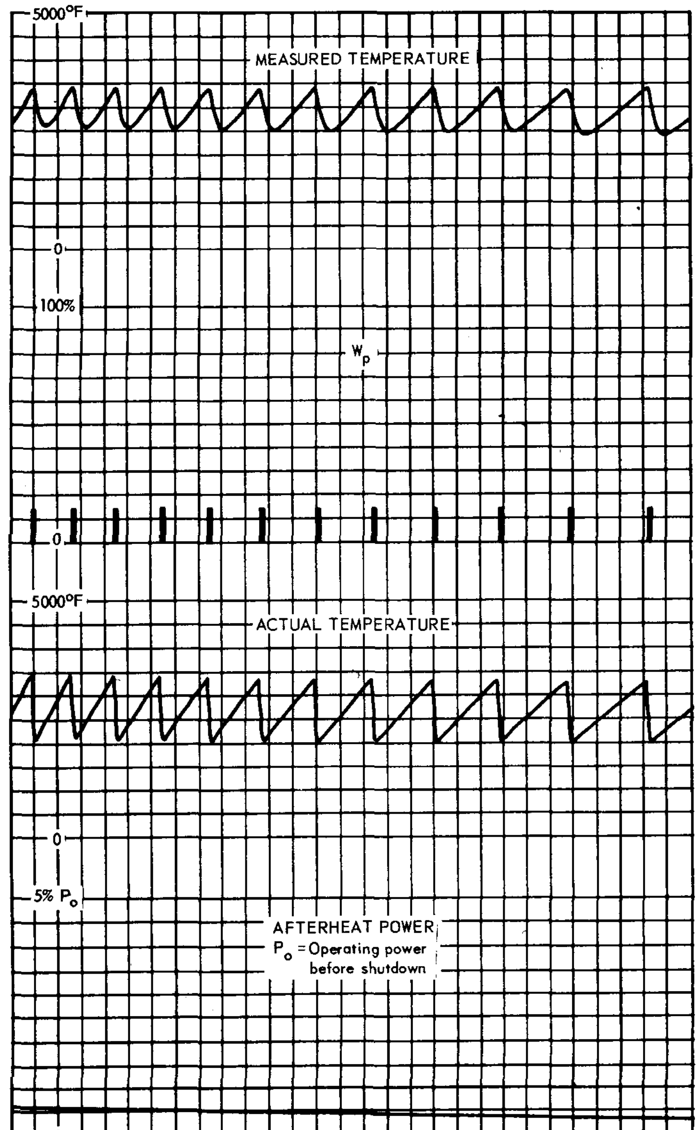


Fig. 11.7 – On-off temperature control of propellent flow during the aftercool period. Note that the measured temperature signal, T_m, and the actual reactor temperature, T_f, are quite different. Temperature sensor time lag, τ = 1.2 seconds

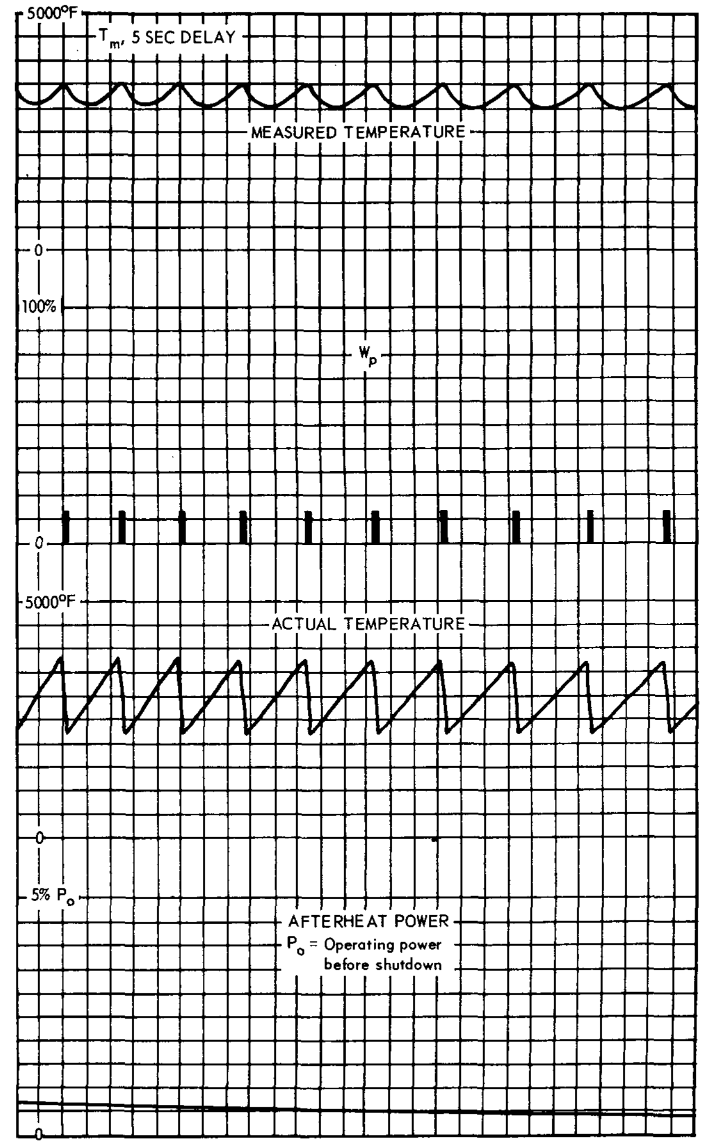
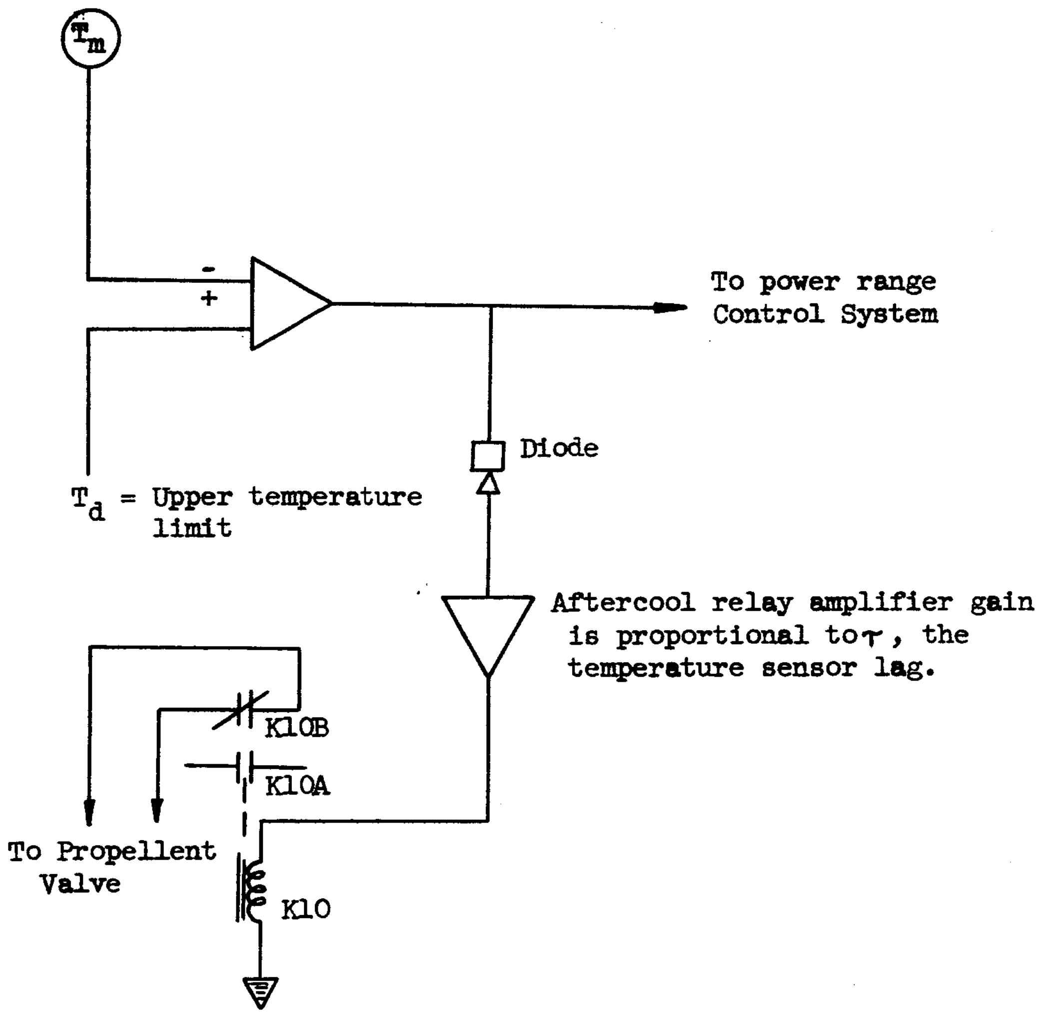


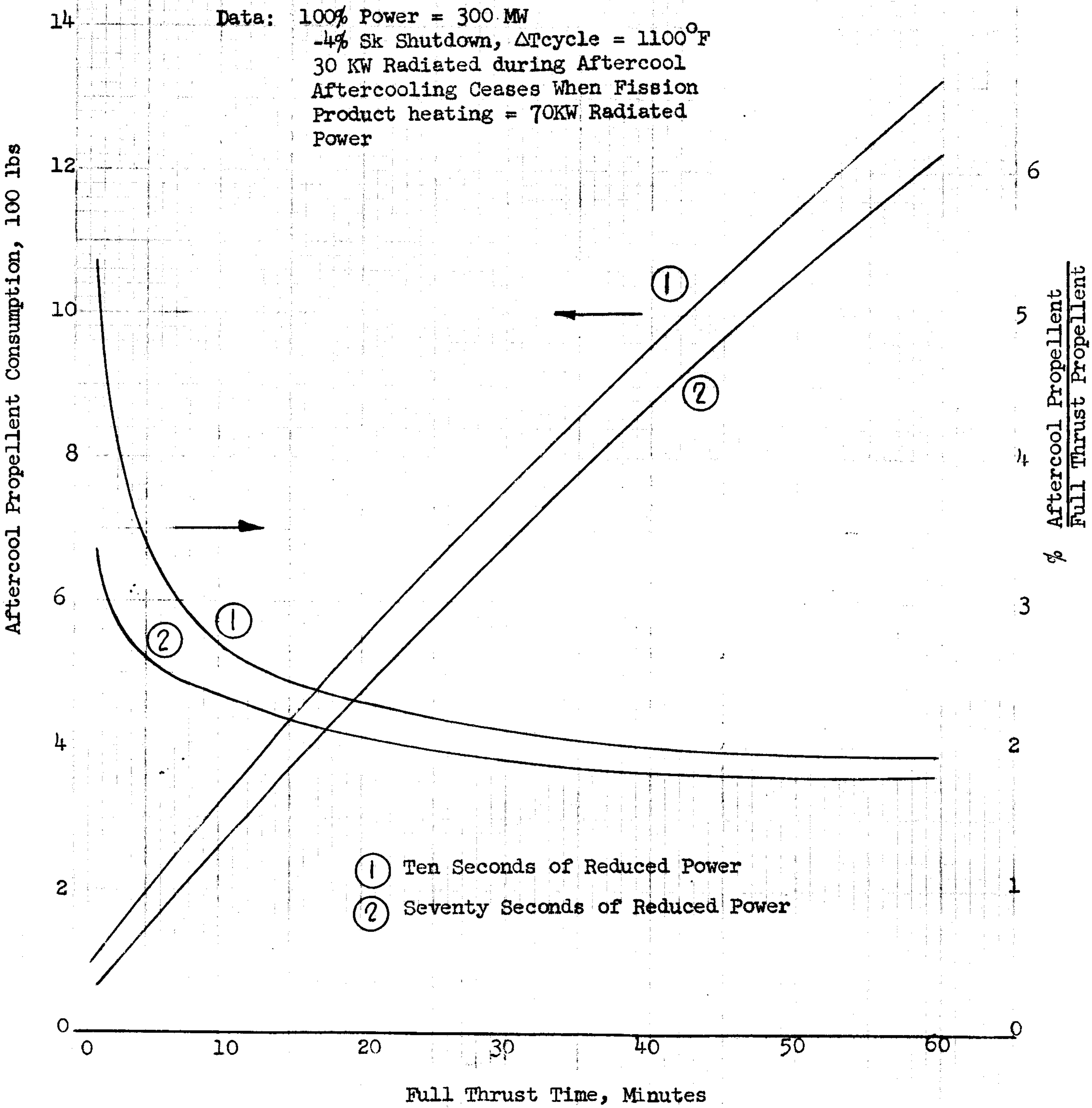
Fig. 11.8 – On-off temperature control of propellent flow during the aftercool period. The instantaneous value of the measured temperature, T_m, is greatly different than the actual temperature, T_f, but the average values are proportional. Temperature sensor time constant =5 seconds.



Note: In practice the relay amplifier may be replaced with a bistable solid state module which controls the propellent valve directly without the intervening relay

FIGURE 11.9 SCHEMATIC DIAGRAM OF AN ON-OFF TEMPERATURE CONTROL FOR PULSED AFTERCOOLING

Fig. 11.10 - Aftercool Propellent Consumption as a Function of Thrust Duration for Two Different Thrust Programs



Delayed neutron heating is effective for only a few minutes after shutdown, and can be substantially reduced if the reactor is made about 4% subcritical. A comparison of the propellant consumption for a 2% and 4% subcritical shutdown is shown in Figure 11.11. There is not much additional saving to be gained by making the reactor more than 4% subcritical.

Aftercooling propellant consumption depends upon thrust duration, power radiated during aftercooling, and the power that can be radiated when aftercooling ceases. Figures 11.12 and 11.13 show that the aftercool propellant consumption for radiation power levels of 10 to 70 KW. The aftercooling period of time depends upon the thrust duration and the power that can be radiated without propellant cooling.

The following statements summarize some of the above observations.

1. When a shutdown occurs delayed neutrons are important source of heat for about 100 seconds. Fission heat sources predominate thereafter.

2. Shutdown reactivity should be $> |-3\% \, \delta k|$ to reduce delayed neutron heating and aftercooling requirements.

3. Fission products and delayed neutron power decay considerably if the thrust is reduced to 10 or 20% of design value about a minute before shutdown. Aftercooling pulse rate and propellant consumption are thereby reduced especially for short duration thrust runs.

4. Higher thermal radiation levels reduce the propellant consumption considerably for long duration runs (10 minutes or more), but somewhat less for short duration runs, (2 to 5 minutes).

5. The time between shutdown and final termination of all aftercooling is greatly dependent upon the thermal radiation level that can be achieved without exceeding design temperature limits.

6. Longer thrust runs (10 to 30 minutes) use a smaller percentage of the total propellant for aftercooling than short duration runs of less than 5 minutes.

7. A reactor scram from 100% power should be avoided when possible, but if it is necessary, the propellant flow should also be reduced. The propellant flow should approximately follow the reactor power to avoid rapid changes in temperature.

12. Programmer Functions

A selective programmer acts as a translator of information from the navigation and guidance system to the thrust control system. The sequence and control of the reactor and propellant feed system are supervised by this important unit. Definite

Fig. 11.11 - Aftercool Propellent Consumption

Conditions: Q = 300MW, F = 15K #, ΔTcycle = 1100°F

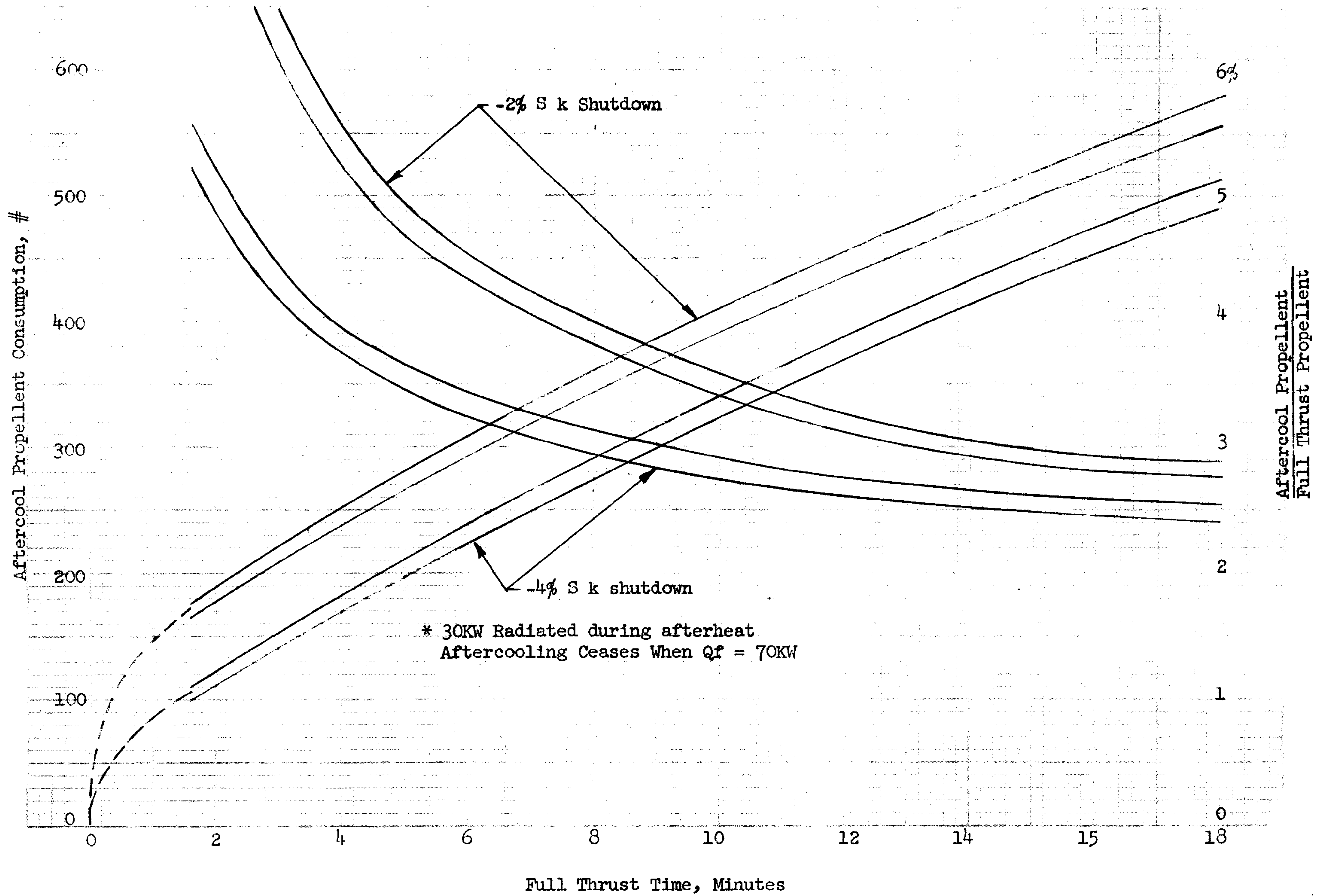


Fig. 11.12 - Aftercool Propellent Consumption as a Function of Thrust Duration for Various Thermal Radiation Levels During the Aftercool Period

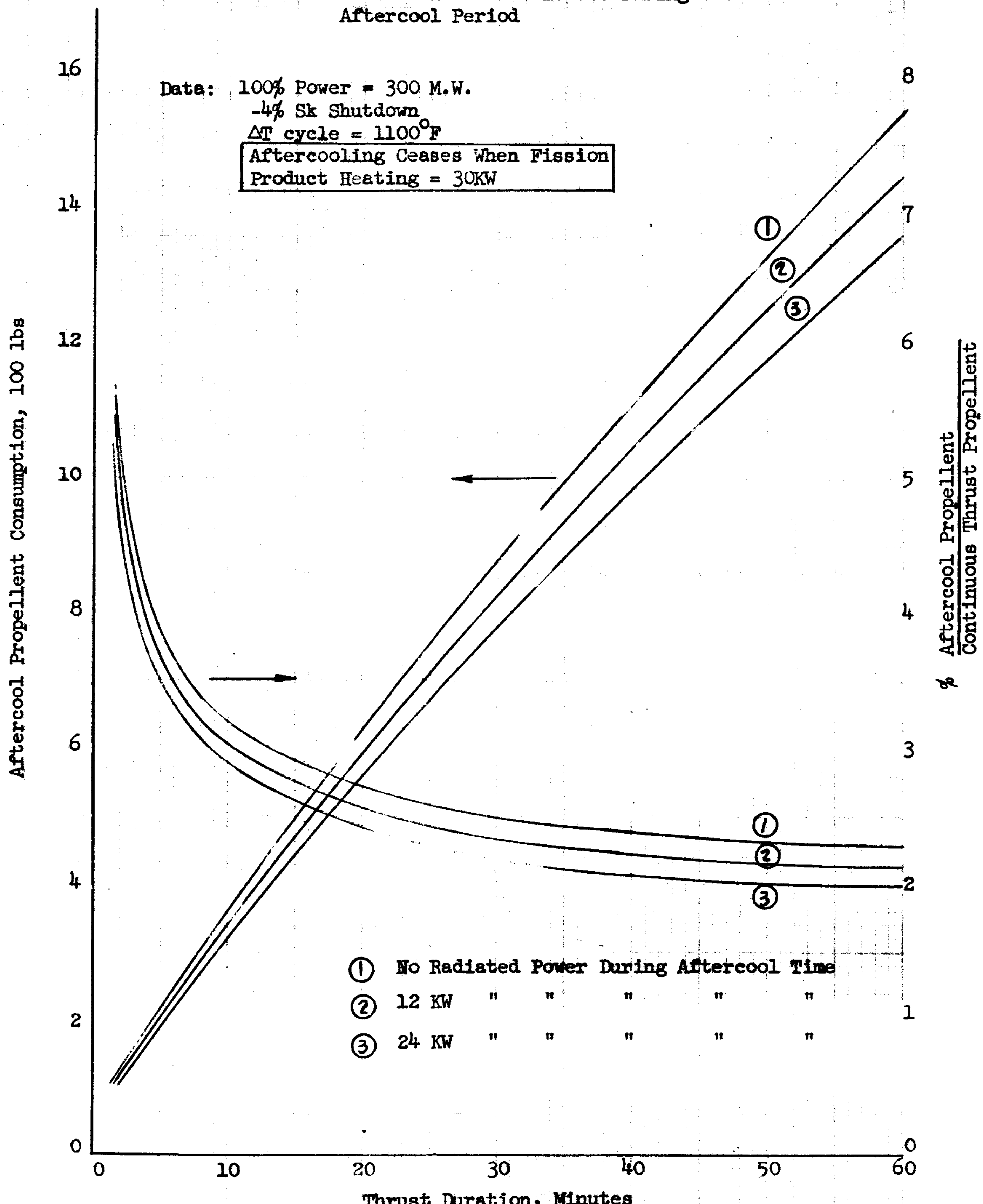
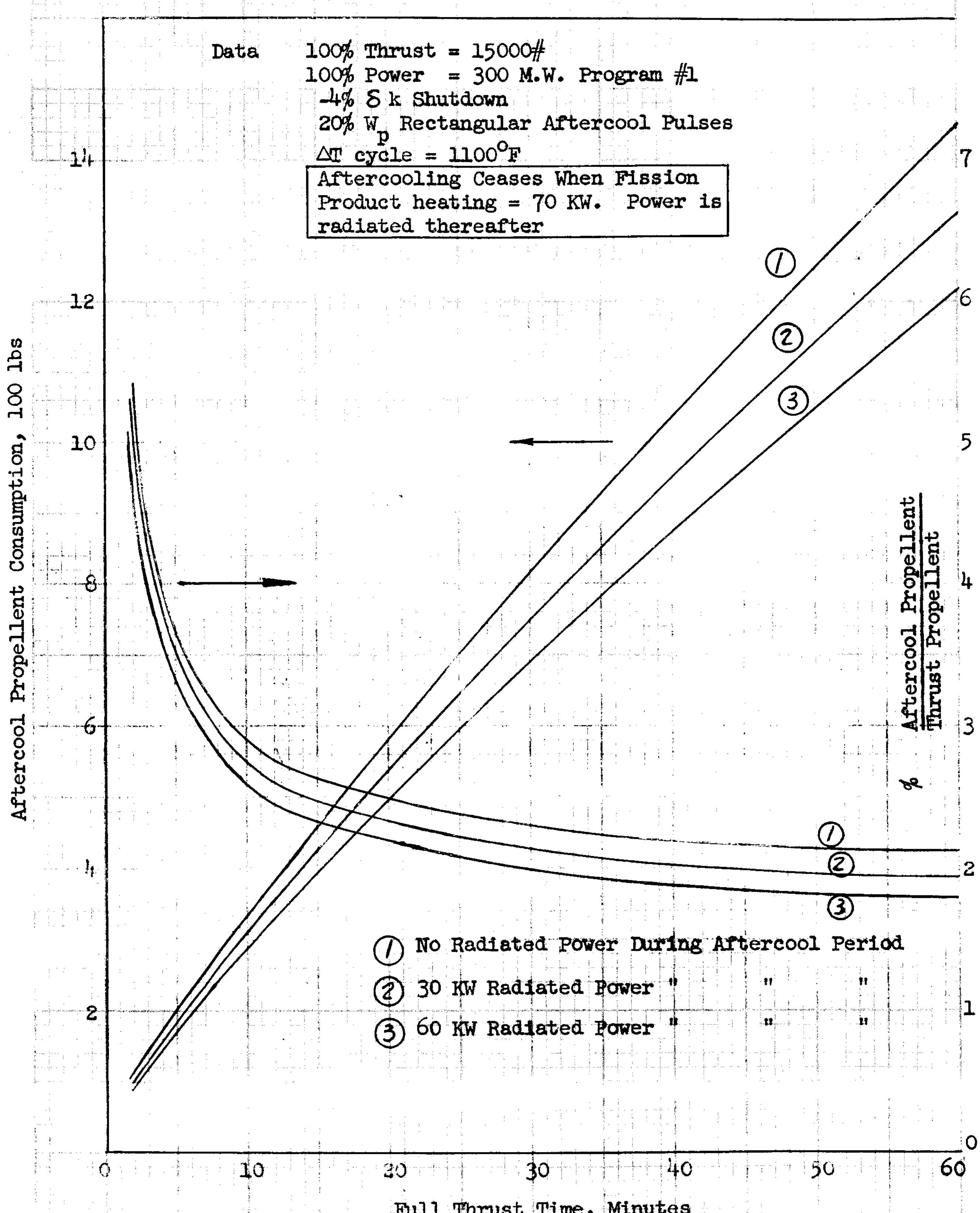


Fig. - 11.13 - Aftercool Propellent Consumption as a Function of Thrust Duration for Various Thermal Radiation Levels During the Aftercooling Period



startup procedures, interlocks, and programming schedules are contained within this unit. Some of the functions that are initiated or controlled by the programmer are listed below without reference to the detailed steps.

12.1 Reactor startup logic functions

(a) Initiate a reactor startup upon command from the guidance system.
(b) Remove the reactivity limit at the appropriate time during this startup.
(c) Schedule the reactor flux when an ion chamber provides a usable flux signal.

12.2 Turbopump startup logic functions

Prior to engine startup it is necessary to start the turbine and prepare the propellant feed system for a rapid engine startup.

(a) Valves are sequenced and controlled to start the turbine.
(b) The transition to turbine speed control is supervised by the programmer.

12.3 Engine startup logic operations

During a rapid engine startup, propellant control valves must be opened in sequence as the reactor temperature or power reaches predetermined levels. Reactor flux and propellant flow must be programmed to prevent under and over temperatures of the reactor.

(a) Initiate an engine startup when all conditions are "go".
(b) Supervise the transition to automatic speed control of the turbine on a hot gas or heated bleed system.
(c) Schedule reactor flux, temperature, and turbine speed. Initiate and schedule propellant flow when the reactor flux or temperature is sufficiently high.

12.4 Power range maneuvers

Schedule thrust control system variables to provide a desired thrust modulation. Acceleration and deceleration schedules are prepared and stored in the programmer. A command to go to full thrust or to reduce thrust is supplied from the guidance system.

12.5 Terminate thrust

The guidance system supplies a signal to reduce thrust to a low hold value. After a minute or so at low thrust the guidance system initiates a reactor shutdown. The programmer then schedules propellant flow to follow the reactor flux. Propellant flow is controlled during the aftercool time so that reactor temperature remains in bounds.

(a) Programmer reduces thrust on a predetermined schedule upon command from the guidance system.
(b) Programmer holds thrust at a predetermined low level until the guidance system initiates a reactor shutdown.
(c) Propellant flow is scheduled and controlled to maintain reactor temperature within acceptable limits during and following the shutdown.
(d) Programmer is automatically reset for the next possible startup. Valves are shut off in a logical sequence.
(e) Aftercooling is terminated when fission product power has decayed to values that can be radiated into space without engine damage.

There are may detailed interface steps that the programmer must perform. Every function that an operator must logically perform is a part of the programmer. This unit will be fairly complex and must be designed for high reliability.

13. Concluding Summary

Section 1. discusses some of the factors which influence the thrust control system requirements of a nuclear powered vehicle based upon several different missions. Some general propulsion control system requirements are given in Section 2.

Rocket engine operation is classified in four phases according to the sequence performed. These phases include (1) reactor startup, (2) engine startup, (3) engine thrust control, (4) engine shutdown and aftercooling. A programmer is required for sequencing and phasing the transition between operations.

The most important part of a thrust control system is the sensors which supply the measurements because the accuracy and reliability of an automatic control system are often limited by its sensors. Rocket engine variables such as pressure, temperature, flux, reactivity, turbopump speed, and propellant flow may be considered in designing a thrust control system. Practical considerations may eliminate the measurement of some of these variables. Section 4. discusses these measurements and the required sensors with relation to thrust control systems. There are many different possible ways of using these measurements in designing a thrust control system.

Reactor startup characteristics are determined by the reactivity and neutron generation time. There is little difference between the startup characteristicss of a fast spectrum and thermal reactor if the reactivity, $\delta k \leq 0.8\beta$ A reactor has inherently exponential characteristics and responds best to exponential or parabolic schedules.

Hot bleed or heated bleed turbopump dynamics also exhibit an exponential behavior. Engine schedules must be designed to prevent operation in the surge region and yet allow operation in the higher efficiency pump region. Turbopumps for rocket engines are designed so that nearly all of the operating load line lies inside the permissible operating region. This allows a wide throttling range.

Reactor and engine startup control should be an integral part of the main control system to minimize the number of components and thereby increase reliability and reduce weight. There are several possible approaches and the selection of a given system depends upon sensor design limitations and the control system sophistication that may be desired. Selection of the main control system parameters greatly influences the startup system design.

Although it would be desirable to eliminate ion chambers and the flux measurements in the startup range this is not entirely possible. Precalibrated reactivity elements may be used to make the initial startup but an ion chamber must eventually be used to hold a given flux level before the engine startup begins. There is some possibility that a negative temperature coefficient could be used to do this instead of the ion chamber but nuclear reactors may not have a negative temperature coefficient in the lower temperature range. To guarantee stability during the engine startup, some form of flux measurement must be used. The flux signal may be fed directly into the reset drum position loops or used in a flux loop. The flux measurement must cover the engine startup range of 4 or 5 decades.

Four types of control systems and some of the systems which may be classified in each category are given in Section 9. Some advantages and disadvantages of each system were itemized. The following are a list of observations from an analog computer study of these systems.

1. Drum position loops with an equivalent second order system response of $W_n = 25$ rad/sec and $\zeta = 0.5$ provided good stability.

2. The following reactivity rate limits were satisfactory for all systems considered in the study:

Proportional δ k Control	15% δ k/min
Integral Control	10% δk/min withdraw 20% δ k/min insert
Proportional δk Position Limits	$\pm$ 0.35% δk max

3. Better response is achieved if the flux or temperature loop gain is biased to favor a reduction in power. For a closed loop temperature system a gain variation of 2:1 favoring a reduction in δ k will reduce the transient temperature error considerably.

4. A turbopump speed loop eliminates the necessity of a series propellant flow control valve.

5. To stabilize the turbine speed loop and overcome the effect of the non-linear valve, a position loop around the turbine power control valve (TPCV) is required. A position loop with a natural frequency, $F_n \geq 5$ cps and a damping ratio, $\zeta = 0.5$ was satisfactory for all conditions that were investigated. Full displacement of the valve may be rate limited to about one second without degradation in system performance.

6. A negative temperature coefficient of reactivity, $0.5 \leq |\delta k_T| \leq 5\%$, is highly desirable because controller gain settings can then have a wider range of values and still have acceptable performance.

7. Fission product heating does not affect the power range stability of the control systems that were investigated.

8. For most systems, a positive propellant coefficient aids the controller while a negative propellant coefficient opposes the controller during acceleration and deceleration times. A positive propellant coefficient and a negative temperature coefficient provide the best possible type of reactor for rocket applications.

9. If the reactor has a zero or positive temperature coefficient of reactivity, flux feedback to the drum position loops is mandatory to guarantee system stability under all conditions.

10. Parabolic or exponential thrust demand schedules are preferred over ramp schedules because the maximum deviation is reduced during power range acceleration and deceleration maneuvers.

11. A minimum 10 second acceleration and deceleration time is recommended for power range maneuvers to reduce the maximum reactor temperature deviation. A 20 second engine startup time is recommended if 5 decades in reactor flux must be covered during this time.

12. If exact control of thrust is not required, the power range control system can be simplified. Approximate specific impulse and thrust control eliminates one controller measurement. Exact thrust control is not required if the inertial navigator computes the velocity increment of the vehicle and terminates the powered flight as the velocity increment approaches the correct value.

13. During a shutdown from full power, propellant flow should approximately follow the reactor power until the aftercool control takes over. Time rate of change in reactor temperature is then greatly reduced.

14. Aftercooling can be controlled effectively from temperature measurements. Control from a computed schedule based upon past operating conditions shows very little promise.

There are a number of navigation and guidance problems that arise in performing a rendezvous mission. In general, a rendezvous mission will require a fairly good terminal guidance system and it is hoped that the aftercool thrust may be used effectively during this time. If the nuclear rocket is used to create a centripetal force with respect to the target satellite, we have a planetary system. The target satellite is always protected from the nuclear radiation since it is in the shadow of the reactor shield. Navigation and guidance must be closely integrated with the nuclear thrust control system in order to perform these maneuvers successfully.

A selective programmer acts as a translator of information from the navigation and guidance system to the thrust control system. The programmer contains the startup procedure or instructions, conditional interlocks and thrust control system schedules. Sequence and control of the reactor and propellant feed system are thereby supervised during all four phases of the engine operation.

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